

# **Validation of Experimental Approaches in Forensic Science: a Case Study of Tissue Fragments Created during an Explosive Event**

**A thesis submitted for the degree of PhD in Security and Forensic Science**

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## **Declaration**

I, Erin Kathleen DuBois, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

## **Abstract**

The field of forensic science is currently shifting away from employing personal experiences of expert witnesses to form the bases for evidence interpretation to one that is more firmly based on scientific evidence. This extends across the field of forensic science, including investigations concerning explosive events. In order to better understand what occurs during an explosive event, realistic experimentation is required in order to build up a strong evidence database that can be applied to forensic investigation by researchers and practitioners alike. To work towards this aim, in this thesis several primary experiments were conducted to explore the use of different materials and material target sizes in experimental explosions. The rationale was that changing and downsizing materials would facilitate use of this type of experimentation and encourage build-up of the evidence base. Three sets of primary experiments were conducted which examined three different materials and material target sizes; scaled piglets, large gelatine blocks and scaled gelatine blocks. The results from each of these experiments were compared to the more standard large pig experimental model, to identify the similarities and differences between the two data sets. The development of appropriate quantitative methods is also a key concern in forensic science. To address this, the comparison of the data sets was conducted using a bespoke statistical program written in R studio, which was designed for easy use and interpretation and could be modified for a range of experimentation comparisons. A further key concern is the real world validity of forensic experimentation. During the course of study, the author had the opportunity to get involved with a large-scale police training exercise in which a bus was exploded. This enabled her to explore the implications of a more realistic post-explosive setting and make comparisons with her own experimental findings. Results were coupled with a set of interviews with law enforcement practitioners to explore the everyday use of forensic science in the field. Thesis results highlighted that large pig explosions produced data that was most similar to what would be present on an actual explosive event scene. The adapted explosions showed some promise, although more testing would be required to produce a sufficiently powerful statistical examination of each of the materials and material target sizes. Results also indicated that the input of practitioners is key for the development of realistic experimentation.

## Impact Statement

Forensic science is an important aspect of any criminal investigation. In recent years, however, this field has come under criticism for the lack of scientific evidence backing up certain claims. This research was designed to address this wide-ranging issue by focusing on one aspect where systematic evidence is lacking, the spatial distribution of tissue fragments created during an explosive event. This research explored various different materials types that could be employed in this type of forensic experimentation that are easier and cheaper to obtain than those in more standard use. The reasoning was that easier, comprehensively documented experiments could open up the potential to develop a significant evidence base in the field. It is through more experimentation that a true scientific understanding of this area of forensic science can be fully explored. Whilst the research showed some potential for using alternative materials, such as gelatine for representing biological targets, the experiments showed too many differences to confirm this and more experiments would be required in the future to give a reliable assessment. Despite being non-conclusive, this research has made an impact by setting up a process by which easier experimental replication is possible and hence should act as a reference for academics and forensic scientists hoping to study in this area.

In terms of product development, to analyse the data collected during the ranges of experiments, a statistical program was developed to compare and contrast various elements within each separate experiment. This program was developed with external use in mind, as it is hoped that it can be used by practitioners in the field of criminal investigation to produce a more in-depth understanding of what may have occurred directly before the explosive event. It is also hoped that this program will be used to help identify characteristics of a particular explosive event that may be similar to others that have occurred in the past. This could aid in the identification of who may have conducted the event as part of an investigation and potentially help lead to their eventual prosecution in a court of law. Through the course of this research, contacts were made with various law enforcement practitioners. It became clear that working relationships, such as those established here, are necessary in continuing to provide a real world influence and use of this type of research-based forensic experimentation in the future.

The research reported in this thesis has been disseminated in a number of ways. Firstly, ideas have been shared with practitioners through their involvement in the experimentation and through interactions as part of the bus explosion training exercise reported in Chapter Eight. Secondly, the findings were presented at the following conferences: Australian and New Zealand Forensic Science Society (ANZFSS) 23rd International Symposium on the Forensic Sciences 2016, the Chartered Institute for Archaeologist (CiFA) Annual Meeting 2016, the 81st Annual Meeting of Society for American Archaeology (SAA) Conference 2016, and the 7th European Academy of Forensic Science (EAFS) Conference 2015. Finally, some of the early methodological PhD work was disseminated through an academic publication 'Forensic Science



International' under the title 'An Examination of the Spatial Distribution of Tissue Fragments created during an Explosive Event'. There is the potential for other academic publications, such as a research article using the R program to compare the behaviour of the different materials in explosions.

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## List of Definitions

**Detonation:** occurs when the explosive chemical material reaches the temperature at which it explodes (Akhavan 2004)

**Deflagration:** the process in which the explosive material is triggered to release its energy by the resulting shock wave (Edwards and Clasper 2016)

**Shock Wave:** In the terms of the information contained in this thesis, it is a pressure wave that travels through the explosive material providing the energy for the explosive chemicals to detonation (Akhavan 2004)

**Blast Wave:** In the terms of the information contained in this thesis, it is a pressure wave that travels out from the explosion through the surrounding environment (Akhavan 2004)

**Rarefaction:** In the terms of the information contained in this thesis, rarefaction refers to the reduction of the blast wave density (Akhavan 2004)

**Total Station:** Used to collect a three-dimensional spatial map and assigns a field specimen number to the evidence

**FBI:** The Federal Bureau of Investigation, the principal federal law enforcement agency in the United States. It is also a domestic intelligence and security service (fbi.gov)

**ATF:** A United States federal law enforcement agency that is responsible for investigating and preventing federal offenses involving the illegal use, manufacture and possession of firearms and explosive; acts of arson and bombings; and the illegal trafficking of alcohol and tobacco products (atf.gov)

**EOD:** Explosive Ordinance Disposal, involved in defusing all types of unexploded ordnance which can range from improvised, chemical, biological and nuclear (atf.gov)

**Law enforcement personal/Practitioners:** In the terms of the information contained in this thesis, refers to individual/s involved in the criminal investigation. Throughout this thesis, the term *practitioners* is employed as a shortened means of discussing *law enforcement personal*

**Forensic scientist:** In the terms of the information contained in this thesis, refers to individual/s involved in the analysis and interpretation of evidence collected during a criminal investigation

**-Research scientist:** In the terms of the information contained in this thesis, refers to individuals involved in research associated with improving evidence analysis and interpretation to better aid those in a law enforcement role. Throughout this thesis, the term *forensic scientist* is used to include and describe research scientists who conduct research into the various sub-fields of forensic science.

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## **Chapter One. Introduction**

The field of forensic science is currently undergoing a paradigm shift regarding how evidence is located, collected, analysed, interpreted and presented in a court of law. There is a movement in the field away from relying heavily on personal experiences to inform evidence interpretations that could be subject to bias and towards a focus on using empirical evidence to inform interpretations. This shift was ignited by the landmark report published by the National Academy of Science in 2009 (Mnookin et al 2011, 11; Edwards 2010, 8; Edwards 2009, 7-8; NAS 2009; PCAST 2016) that highlighted the lack of empirical based data and focus on personal experience that forms the bases for evidentiary findings within the field. Several following reports have arrived at similar conclusions and are outlined in Table 1.1.

Report Published By	Year/Country of Origin	Key Findings
Government Chief Scientific Advisor (GCSA)	2015/United Kingdom	New capabilities to analyse data, but have outpaced forensic scientist ability to interpret
Forensic Science Regulator (FSR)	2015/United Kingdom	No clear interpretation standards in many areas of the forensic sciences
Toronto: Centre for Forensic Science and Medicine	2013/Canada	Continuous and sustainable improvement in all the disciplines of forensic sciences required
Independent Review of the National Institute of Forensic Science	2014/Australia	There is an inability to understand, evaluate or properly employ expert evidence

**Table 1.1.** A list of several international reports that have come to similar conclusions stated by the NAS 2009 report.

This lack of empirical based data has led to many recent criminal cases being retried or thrown out completely due to new scientific information revealing that personal biases led to incorrect interpretation of the presented evidence (Saks and Koehler 2005; Cole 2006; Bowers 2006; Christensen and Crowder 2009). This has led to a rise of criticism and lack of trust associated with the field of forensic science (NAS 2009; PCAST 2016; GCSA 2015; Edwards 2009; Risinger 2009; Pollanen *et al.* 2013; Vincent 2013).

One area within forensic science where this lack of empirical evidence is present is in the area of explosives, and specifically in relation to terrorist attacks like suicide bombings. This is significant given the increase of terrorism-related bombings across the world (Quillen 2002; Arnold et al. 2004; Morley and Leslie 2006; Wolf et al. 2009). In

recent months across the Western world, explosive-related terrorist attacks have been less visible as cars, knives and guns are being used with more regularity (Government Digital Services 2017). However, these types of terrorist incidents are still very relevant. For example, a suicide bomber was responsible for the 2017 Manchester concert bombing (BBC News 2017). It should also be noted that in many areas around the world terrorist attacks often employ the use of explosives, like the truck bombing in Kabul Afghanistan in May 2017 which killed 80 individuals (Mashal, Abed, and Sukhanyar, 2017). When such attacks do occur, lack of a reference base about what actually happens mean that investigators on the ground often have to rely on their personal experiences to draw conclusions on where to conduct search and recovery efforts, along with how to interpret the collected forensic evidence.

This thesis aims to address this gap by beginning to develop an easily applicable evidence base that examines explosive events through the use of realistic experimentation. This overarching goal will be addressed through using experimentation covering five separate research questions. The research questions for this PhD were:

- 1: Can data from scaled tissue fragment experiments be used to develop more evidence-based search and recovery methods?
- 2: Can gelatine be employed as an alternative tissue target to biological matter in tissue fragment explosive experiments?
- 3: Do tissue fragment experiments with restricted variation present provide enough data that can be reliably applied to real world events?
- 4: What is the best process for comparing and contrasting the data gathered from each of the different tissue fragment experiments?
5. How valuable do law enforcement practitioners find forensic experimentation and resulting evidence?

This thesis is structured in the following manner: the initial literature review outlines the gaps within the current literature that helped to form the overarching research questions. Relevant literature is considered that relates to the understanding of the current field of forensic science, the rise of terrorism and its implications for forensic science, the use of forensic archaeology in forensic investigation, as well as the relevant explosive research. The subsequent chapter states the five research questions with a rationale for

why they are relevant in furthering our forensic understanding of explosive events. The methods chapter outlines how the experimentation that was conducted over the course of this research was designed and how the scaling of both the target materials and the explosive amount was addressed. The next chapter addresses one of the five key research questions-how might we best compare and contrast the evidence patterns across different explosive events? The statistical methods developed in this chapter are then used throughout the remainder of the thesis. The experimental element of this thesis uses animal models to replicate explosions involving human beings. The animals (in this case deceased pigs) are placed at the centre of the explosion and represent the suicide attacker. The use of pigs within this manner is common not only in the wider scientific community but also in forensic science and wound trauma studies (Fackler 1986; Aulick *et al.* 1981; Schoenly *et al.* 2007; Catts and Goft 1992; Passalacqua and Fenton 2012). In the initial set of experiments large pigs were used as replacement for human subjects (see Appendix A). The advantages and disadvantages of using such animal models are discussed here and throughout the thesis.

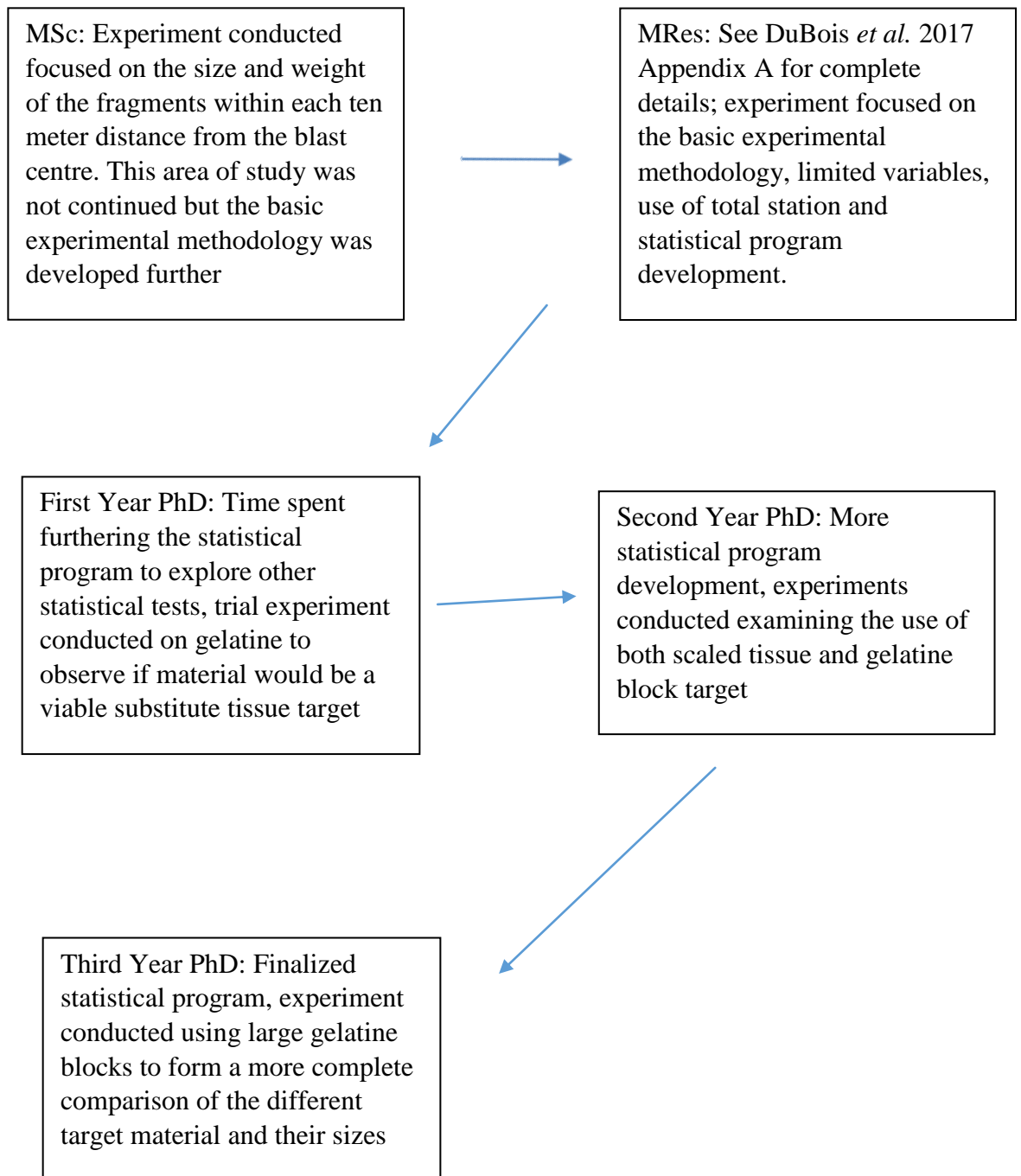
One of the issues with such experimentation is the replicability due to the high cost and large scale undertakings that are often associated with this type of experimentation. As is argued in depth below, for sufficiently reliable evidence bases to be generated, forensic science needs to develop methods for increasing the efficiency of experiments from both a time and financial cost perspective. Hence the experiments in the main body of the thesis are set up to test systems of doing this and in all cases compare results to the original large pig experiments from Appendix A. The first set of experiments examines the use of biological tissue models, but also explores whether scaling the targets by making them smaller still produces similar spatial results. The second set of comparisons looks at using different target material at full scale size to identify if different material types produce similar spatial results. Specifically, they compare the gelatine to the pig cadavers. Lastly, the third experimental comparison combines these ideas and examines whether a different target material (gelatine) when scaled to a smaller size is still comparable to the large pig experiments.

A further issue with forensic experiments is the degree to which they are realistic concerning the conditions of a real forensic scene. Experimentation often involves simplifying contexts, and whilst this can assist with comparison and generation of evidence this could render results less valuable in practice. During the course of this

research, the author developed a number of links to those in forensic practice with the American FBI (Federal Bureau of Investigation). The author was invited to participate in a large scale police training exercise in which a full size bus with an animal model was exploded, as a representation of a likely terrorist setting. This gave the author an opportunity to observe how the data collected from her own controlled experiments compared to that from a more realistic explosive attack situation. The FBI bus experiments gave the author the opportunity to discuss the role of forensic evidence bases in investigation, detection and courts with practicing forensic scientists. Hence in the chapter that follows, the responses to a questionnaire are discussed to explore how forensic science is viewed and employed by practitioners. Lastly, the discussion chapter aims to explore what was learned and achieved through the combined use of experimentation and interviews.

The results obtained through the course of this PhD, demonstrated that the large pigs cadavers (used in a pilot study; see DuBois et al 2017 and Appendix A) produced data that was most similar to humans. Although several alternatives were investigated, when the overall data sets were compared, neither the gelatine (scaled or not scaled) nor the piglet cadavers produced similar enough results to those obtained by the large pig cadavers. It should be noted that these experiments were but a first step in the development of a realistic experiments that can be used to create a workable evidence database that can be easily applied by both practitioners and scientists. The methodology that was developed to both design the experimentation process and the data analysis should continue to be used in more experiments designed to examine alternative target material methods. The close ties that were developed with the practitioners over the course of conducting these experiments helped to not only develop links with those who are involved with the everyday investigation process but also in starting to form a better understanding of what needs to change in order to develop better working relationships with practitioners. It is with better working relationship between researchers and practitioners that experiments can be designed to include more realistic elements, address issues within the field that need to be addressed, and create an environment where both sides in the forensic investigation can be open with each other. The next stages that should follow this work are more experimentation. This will aid in building on the research that explores alternative target materials in order to open up this field of research to more researchers and practitioners. As a whole, the aims of this PhD is the

development of an evidence base built on realistic experimentations. The following page provides a flow chart in which the experimental development that began in during a MSc degree through the PhD (Figure 1.1) to provide the reader with a clear idea of the overall unique experimental design.



**Figure 1.1.** A flowchart that outlines each step in the experiment and methodology development. This includes experiments that occurred outside of the PhD but were nevertheless key in the process of this research.

## **Chapter Two. An Examination of the Field of Forensic and Explosive Processes**

This thesis aims to use experimental research to build a better understanding of explosive events with the goal of assisting practitioners in evidence collection and interpretation. To achieve this aim it is important that an understanding of not only research on explosions and the implications of such events is gained, but also that there is discussion of how the field of forensic science as a whole addresses the concept of evidence collection and interpretation. The following chapter will therefore be split into five sections. The first will look at how forensic science currently addresses the issues surrounding evidence collection and interpretation; it will conclude by applying these concepts to the particular research context of explosions and explain how the research will speak to the challenges raised. Second, the implications and challenges associated with collecting forensic evidence after terrorist attacks involving explosives will be discussed in the particular context of the rise in, and variability of, such attacks. The third section will examine how forensic archaeology can be utilized in addressing the challenges associated with the unknowns often involved in an explosive event. Next, the complexity of the explosive process will be discussed to outline the challenges that arise when examining this particular sub-field of forensic investigation. Lastly, the relevant research in the area of forensic explosive investigation, including the use of animal models, will be examined to highlight the gaps that currently exist in the field. The goal of this section of the thesis is to highlight the importance of conducting the research proposed.

### **2.1 Understanding the current field of forensic science**

The aftermath of an explosive event is very likely to require investigation. This will be particularly true if the event was the result of a terrorist attack. In such situations it is likely that forensic scientists and others will be employed to collect evidence at the



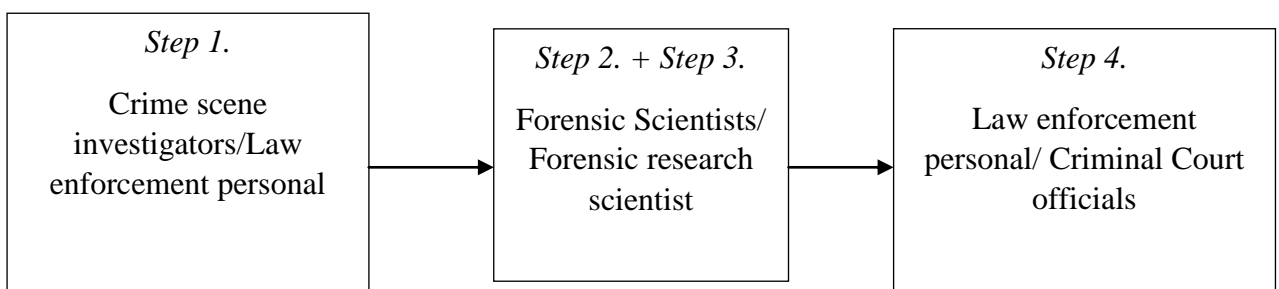
scene and make judgements about how the evidence could be interpreted. It is also possible that evidence from such an event might be used in a court of law. The collected evidence can also be used for intelligence purpose to aid in identifying who conducted the explosive event. All of these activities are part of the forensic science process and it is therefore important that the stages and practices of forensic science are understood.

### 2.1.1 The forensic process

The general goal of forensic science is to explain, reconstruct or predict evidence (Morgan and Bull 2007). Within the field of forensic science there is a conceptual framework that can be applied to various aspects of forensic inquiry, ranging from investigations to research which can be broken down into four necessary steps of the forensic process:

1. An investigation of the scene
2. Analyses of the evidence/data collected
3. An interpretation of that evidence/data
4. Presentation of the both the findings and the associated interpretations to the appropriate parties

In each of the four steps listed above, various individuals are involved in conducting the activities associated with the forensic science process. The flow chart below (Figure 2.1) presents a simplified version that highlights where those various individuals fit into the forensic science process.



**Figure 2.1.** A flow chart outlining the various individuals involved throughout the forensic science process.

Good forensic science practice should focus on at least one of these elements, and also aims to be exclusionary when it comes to evidence analyses and interpretation rather than associative (Morgan and Bull 2007, 50). In this exclusionary philosophical approach the first step is focusing on the nature of inquiry. In this stage the focus is on what evidence should be examined/collected and which should not; this can include both evidence on the macro and the micro scale. This decision should be based on the nature of the overall investigation. The decision as to what is important and what is not will determine what is analysed, interpreted and presented throughout the investigation (Morgan and Bull 2007, 51). The second stage is the practice of analysis. Here focus is on the actual collection and processing of the evidence that was selected in the first stage (Morgan and Bull 2007, 51). How the evidence is collected and processed will determine not only how this evidence is later analysed and connected with other pieces of evidence but also how it will be later interpreted in relation to the overall forensic investigation (Morgan and Bull 2007, 51).

The next stage in following this approach is the interpretation of the results of the collected evidence. It is in this stage of the approach that the complexity that is associated with the uncertainty and individual bias that exist when it comes to attempting to interpret the findings oftentimes becomes an issue. Personal bias associated with what the investigator thinks may have happened needs to be placed aside and with an understanding of the dynamics of the evidence, a decision should be made that is an evidence-based interpretation. This evidence-based interpretation can then be applied to the findings associated with the evidence at a particular place at a particular time (Morgan and Bull 2007, 52). Lastly, the fourth stage of this philosophical approach is to present the results to the appropriate parties in a fair and unbiased manner. The role of the forensic scientist is not to come up with a story of what happened but present the findings of the evidence in an empirical manner - to tell the objective facts in an unbiased manner and not with biased opinions involved (Morgan and Bull 2007, 53-54). Although expert opinions are often used throughout the forensic science process, it is important that those opinions are informed by data rather than personal opinion.

As outlined above, the interpretation of the evidence collected is one of extreme importance, especially when evidence will be used within a legal context. Within this

legal context it is important to consider different propositions which represent both sides of the law (Cook *et al.* 1998, 232). The idea of using propositions can be broken down into a three-level hierarchy. The first (level I) is the simplest level of propositions. This level has a focus on the source of the evidentiary material and is based on the observations, measurements and analyses of the evidence (Cook *et al.* 1998, 233). The probability of evidence association is gained through a careful comparison of the probability of occurrence. An example of this would be A1: the broken metal came from the car door or A2: the broken metal came from another source. The probability of each is determined in this case from looking at a collection of metal references (different types of metal that can be used to compare and contrast to the evidence) (Cook *et al.* 1998, 233).

The second level (II) of proposition is related to activities. This level also uses observations, measurements and analyses but needs to take into account the probability of evidential transfer and persistence. In using the above example of the broken metal, in this level the proposition would be: B1: Mr A broke the car door or B2: Mr A was not there when the car door was broken. This would be addressed by examining the probability of finding the same types of evidence if Mr A was the person who broke the car door and the probability of finding this same type of metal if Mr A was not present when the car door was broken. To help answer this question an examination of any previous research or evidence can be undertaken to draw conclusions. One important difference between level I and level II is that in level II there needs to be a framework of *circumstance*. In the above example, the time between when the car door was broken and when the clothes of the suspect (which may have trace evidence of the metal from the car door) were collected would need to be known, along with how the car door was actually broken (Cook *et al.* 1998, 233). This degree of judgement can only be possible with some sort of interaction between the investigator, advocate and scientist (Cook *et al.* 1998, 233).

Level III is the top level of the proposition and is related to the actual offence. This level of the hierarchy is directly linked to what a jury would have to decide in a court of law, whether the person being accused of the crime actually committed the offence in question (Cook *et al.* 1998, 233). In the course of the above example: C1 would be that Mr A broke into the car or C2: that another person broke into the car, so in the simplest of terms whether a crime was indeed committed by Mr A or another individual. The

difference between level II and level III is that level III is completely outside the domain of the scientist; this is a decision that a jury in a court of law would come to. A scientist may help in explaining the evidence and the likelihood of certain propositions occurring, but the ultimate decision is not the scientist's to make (Cook *et al.* 1998, 233).

In interpreting results, another key principle is the understanding of the dynamics of the evidence so that it is possible to make an evidence-based decision about the significance of finding the evidence in a particular place at a particular time (Morgan *et al.* 2009). This can be achieved through the use of experimental research. In conducting experiments that closely resemble forensic reality, how forensic evidence is created can be examined and explored. This knowledge of the significance of various types of evidence is important for developing more accurate procedures associated with both collecting evidence and understanding the probable location of evidence (Morgan *et al.* 2009). However, this can only be maintained through a constant stream of communication between all of the parties involved in the forensic process. This allows for the information obtained on the significance of evidence to be shared with the appropriate parties within the forensic process. Likewise, these evidence bases on which this information is obtained need to be kept up to date with new techniques that can be applied to evidence collection. This provides valuable information on the significances of evidence to the appropriate parties within the forensic process. This type of information is important for establishing search and recovery priorities, especially on complex and time consuming forensic scenes like a terrorist bombing.

Through a combined use of the conceptual framework, philosophical approach and the hierarchy of propositions, forensic evidence can be selected, collected, interpreted, and presented in an unbiased and empirical manner. In following these processes the sometimes overwhelming forensic investigation can be broken down into parts, ensuring that each section is performed to a high standard and in an impartial manner. This lack of biases is important in arriving at an interpretation that is based solely on what the evidence findings suggest, not what those involved want the evidence to suggest. These procedures should therefore be applied to any forensic science practice, irrespective of whether it is the collection of DNA trace evidence or the identification of fragments following an explosion.

### 2.1.2 The role of experimental studies in forensic science

One important factor at play in both the application of the philosophical approach and the resulting hierarchy of propositions is the availability of appropriate empirical evidence bases. These evidence bases are used to create more accurate collection/sampling procedures and to identify best practices concerning data analysis in specific forensic contexts (Morgan *et al.* 2009, 284). This is of importance since the existence of an evidence base directly impacts the first two levels of both the philosophical approach and the hierarchy of proposition, both of which will in turn dictate how the overall investigation is conducted.

However, rigorously constructed experimental evidence bases continue to be sadly lacking in forensic practice. This is true across all types of evidence, and as will become clear, explosive remnants is no exception. According to the National Academy of Science (NAS) report published in 2009 which examines the field of forensic science, most of the claims that were being made by forensic scientists in a court of law relied more on personal experience and less on experimental scientific evidence to support their evidence interpretation (Mnookin *et al.* 2011, 11; Edwards 2010, 8; Edwards 2009, 7-8; NAS 2009; Champod 2013). Often the observer will/can change answers and interpretation based on outside information, having a direct impact on the outcome of the third stage of the philosophical approach and level II of the proposition hierarchy (Saks *et al.* 2003, 84; Cook *et al.* 1998, 233). Although personal experience is a legitimate knowledge basis in certain instances, the lack of valid experimental bases in order to back up personal experience means that the issue of personal bias comes into play. This report further states that the development of rigorous research should be of the utmost importance to the field in order to determine the capabilities and the limitations of the field as a whole in a way to combat the influence of personal biases impacting evidence interpretation (Mnookin *et al.* 2011, 5-6). Another important aspect to consider is that the interpretation of any experimental results must be done with extreme caution, as the possibility of false positive and false negatives are very real (Morgan and Bull 2007, 54). In order to address the problem of bias, steps need to be undertaken in which the contextual effects are minimized. In increasing the awareness on the subject of the impact of bias with researchers and practitioners, the addition of blind testing and evidence line-ups will all aid in decreasing observer bias (Saks *et al.* 2003, 87 -89). Another suggestion has been the use of linear sequential unmasking as a way to decrease the impact bias may

have on the evidence interpretation (Dror *et al.* 2015, 1111-1112). This method provides the contextual information (level II in the proposition hierarchy) *after* an interpretation of the trace evidence (level I in the proposition hierarchy). In the application of this method, the interpretation moves from evidence to suspect instead of suspect to evidence (Dror *et al.* 2015, 1111-1112). Government bodies have also begun to provide guidance to aid practitioners (both forensic scientist and law enforcement personal) by suggesting various techniques to reduce bias across the forensic investigation spectrum (Forensic Science Regulator 2014). In conducting more research into forensic sciences and the impacts of evidence interpretation, scientists will not only increase the validity of those interpretations but also help the judicial system in assessing the reliability of forensic evidence to assure that it aids in uncovering the truth (Mnookin *et al.* 2011, 11; Edwards 2010, 8; Edwards 2009, 7-8; NAS 2009).

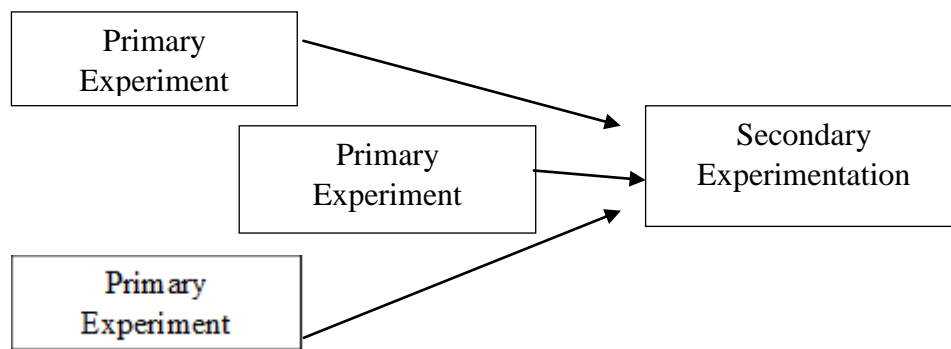
The conclusions about the importance that the role of experimental studies in forensic studies play in developing the appropriate empirical evidence bases was discussed further in the 2016 PCAST (President's Council of Advisors on Science and Technology) report entitled 'Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods'. This report examined what progress (if any) had been made since the ground breaking 2009 NAS report and highlighted two remaining gaps that exist in the field of forensic science. One of these gaps was the continued need for clarity about scientific standards in terms of the validity and reliability of forensic methods (PCAST 2016, 1). The second of these gaps highlighted by the PCAST report was the need to evaluate specific forensic methods to determine if they had been scientifically established to be valid and reliable (PCAST 2016, 1). This concept of validity, in respect to this report, was divided into two parts. The first relates to foundational validity or demonstrating, based on empirical experimental studies, the method to be repeatable, reproducible and accurate at levels that have been measured and are appropriate for the intended application (PCAST 2016, 4). To meet this standard, a method must be thoroughly empirically tested and to meet this need, the report recommends that methods be continuously tested by agencies with no stake in the outcome of the results (PCAST 2016, 5-6, and 14-19).

Within the need for a method to be empirically tested, the use of experimental studies also provides information into assigning evidential weight to evidence. One way this is achieved is through the employment of Bayesian networks. In using Bayesian

logic, forensic scientists are able to provide formal reasoning for the probabilities of different aspects of forensic evidence (Taroni *et al.* 2006). These probabilities associated with forensic evidence can be further explored through the use of empirical experimental studies. Similarly, the use of the likelihood ratios can also be explored in greater depth through the use of empirical experimental studies. The use of the likelihood ratio within forensic science is employed in aiding the determination the probability of obtaining a known sample of forensic evidence and an unknown evidence sample under a known origin verse an unknown origin (Morrison 2011). Once again, an understanding of known origins and known samples can be further developed with the use of experimentation.

The second definition of validity deals with validity as applied, or the extent to which the method has been reliably applied in practice (PCAST 2016, 4). To meet this standard, it must be determined that the forensic examiner has been shown to be both capable of reliably applying the specific forensic method and to have actually conducted the method appropriately (PCAST 2016, 6). Once again, this area of validity relies heavily on experimental studies to provide an idea of the rate of false positives/negatives that can result, along with the sensitivity of the method. This is used as a means to establish not only how to perform the method correctly, but also provides examiners with the tools to correctly interpret the reliability of the results (PCAST 2016, 6, 48). In particular, in order to increase the validity of evidence interpretation there needs to be a development of an empirical evidence base which forensic scientists and others involved in the forensic /legal process can employ to compare and better understand any evidence interpretation results. As noted above (2.1.1), using an evidence base to compare results is important in level II of the hierarchy of propositions (Cook *et al.* 1998, 233). The development of an evidence base requires both primary and secondary experiments that are repeatable and closely resembles forensic reality (Morgan *et al.* 2009, 277). When producing an evidence base, the first stage involves the use of primary experiments that aim to establish a generalized body of theory that characterises the general nature of particular elements under specific situations. In simpler terms, that is to develop a basis of understanding of how certain aspects act in the simplest of situations (Morgan *et al.* 2009, 284). This reflects level I of the hierarchy of propositions or a focus on the trace evidence (Cook *et al.* 1998). It is in these primary experiments that a number of experiments are employed to understand the simplest of situations, since complexity exists in even these

situations (Morgan *et al.* 2009, 278; Morgan *et al.* 2008, 186). In the next stage, to reflect specific case issues, the use of secondary experiments can be employed to examine more complex and individual elements that are associated with specific situations (Morgan and Bull 2007, 54). This is achieved by building on what the generalized body of theory has established in the primary experiments and adding complexity in the secondary experiments (Morgan *et al.* 2014, 50). The flow chart below provides a simplified outline of this concept (Figure 2.2). Evidence bases are important at all stages of the forensic process, including in the interpretation of evidence and robust crime scene reconstruction. Having these evidence bases which can be applied at any stage of the forensic process aids in increasing the overall validity of the process.



**Figure 2.2.** A flow chart outlining how the primary experiments help to build up to the large more complex secondary experiments.

### 2.1.3 Dealing with complexity and variability

As acknowledged earlier (2.1.2), complexity exists even in the simplest of forensic contexts, and again it will become clear later that post-explosion settings are no exception. Not only is a single forensic scene an incredibly complex situation, but there will also be a large amount of variability between even two different forensic scenes (Morgan *et al.* 2009; Morgan *et al.* 2008). The goal of developing an empirical evidence base (discussed in full in 2.1.2) is founded around the concept of developing a theory that is both general enough that it can be applied in a wide range of scenarios, but also be sensitive enough to be applied to an individual investigation context. Although it can be a difficult challenge to replicate real world variations in the necessarily experimental setting, this challenge can be addressed in part by using expert experience from real world practitioners to help develop and conduct experiments. However, no matter how well an experiment is designed and implemented, there is always the risk that the experimental results do not correctly simulate a real world event. One reason is that when an empirical



evidence-base is developed from scratch, the experiments need to focus on building up a primary idea of what happens within the most basic of circumstances. This is done to build up a sound body of theory by examining the most general nature of particular variables under very specific situations (Morgan *et al.* 2009). It is only in the secondary set of experiments where more complex and detailed elements are examined. These experiments are used to build off the body of theory that has been established in the primary experiments and add complexity to the empirical evidence base (Morgan *et al.* 2014). In the case of the experiments that were conducted over the course of this thesis, very restricted variables are present in order to investigate specific questions. Although this research aimed to help develop a sound body of theory that is general enough to address a range of issues, how the results are applied to real world situations is an important question to ask. The most useful empirical evidence bases are ultimately designed to provide practitioners an outline of methods of best practice that they can employ to their particular cases. If experiments are designed without the input of practitioners and how to best address their needs, then the data that is produced is likely to be of limited value to the larger forensic community (Morgan *et al.* 2009).

Additionally, if there is a lack of understanding in why these types of experiments are important to conduct or even in how the experiment process is conducted, then there is a lack of constructive communication that can aid in how the experiments are designed. Forensic science is trying to move away from personal biases towards more realistic experimentation to develop scientifically relevant data to forensic evidence. Having the communication channels open to allow for the input of practitioners is vital to achieving this aim.

This view is reflected upon in the Forensic Science Regulators 2015 annual report, the use of expert experience can be used to help experiments resemble the challenges on the ground (Tully 2015). This also aids in testing (through a strict experimental process) what actually works and what does not with input of those same individual/s who will later go on to actually put these reproducible and transparent methods to use. Whether it is forensic evidence recovery, analysis or interpretation, having the input of the practitioners can aid in developing strict scientific approaches that will also meet the needs of those same practitioners (Morgan *et al.* 2009, 284). Finally, it is worth noting that doing experiments is useful in identifying both what works and what does not (Morgan *et al.* 2009). For example, if an experiment is able to eliminate a certain theory

that is of general use to the field, it is as important as experiments that provide corroborating evidence.

#### **2.1.4 The challenges of forensic science in practice**

As discussed earlier (2.1.1), the forensic process is one that contains a range of stages and many different individuals/groups conducting their own important process within each. This can become a problem since these different individuals/groups often have very different aims, even though the overriding goal of a successful completion to a case is the same. Law enforcement agencies are focused on the quick apprehension of the individual(s) involved in creating the forensic scene or levels 2/3 in the hierarchy of propositions (2.1.1). In comparison, forensic scientists are focused on an in-depth evidence recovery, analysis and interpretation or level 1 /2 of the same hierarchy (2.1.1) (Cook *et al.* 1998). This mismatch can create a problem since forensic evidence and its interpretation are very important to any criminal prosecution (Mnookin 2011, 2). If it is rushed and/or not done properly because of lack of communication or outside pressure, then the overall goal that all parties are focused on will not be achieved. In order to achieve a process in which the many different individuals/groups work together, the ability to have strong and open communications/feedback is paramount. Through effective communication the aims and goals of all parties can be met (Ludwig and Fraser 2014). This open communication and feedback can be related to the above discussion of the use of expert experience in the development of empirical experiments (2.1.3); it is only through an open dialog between the practitioner and the forensic scientist that a process that meets the aims and goals of all parties can be met.

It is not only the struggles that exist internally in the forensic process that can create challenges in the practice of forensic science. Like any field that deals with the wider public and is concerned with their perception of its practice, the impact of the overarching policies can play a huge role in determining its credibility. Recent news stories and court cases have highlighted the failures of forensic interpretations which have led to criminal cases being retried or thrown out completely; one notable example is the U.S. Supreme Court case of *Daubert v. Merrell Dow Pharmaceutical* which came to the conclusion that trial judges have the responsibility to ensure that any scientific testimony presented to a court is relevant and reliable (Saks and Koehler 2005, 894; Cole 2006, 118;

Bowers 2006, S107; Christensen and Crowder 2009, 1212). A more recent example is that in a 7 year period in the United Kingdom 218 criminal cases were successfully appealed on the bases that the forensic evidence employed was misleading (Smit *et al.* 2017) In addition to this, the watershed 2009 NAS report raised additional criticism and questions concerning the strength of forensic conclusions that were being used in criminal cases (Edwards 2009, 7-8; Risinger 2009, 22).

In order to address this rise in criticism and lack of trust associated with forensic conclusions, several commissions (i.e NAS 2009, Government Chief Scientific Advisor (GCSA) 2015) have been made to deal with these concerns. The above mentioned 2009 NAS report calls for the need for greater experimentation to observe what works and does not, along with developing stronger standards of practice in which to apply those results (Edward 2009; Risinger 2009). This focus on an increase in experimental research continues in Forensic Science Regulator (FSR) annual report, which not only established a range of research priorities (recording methods to targeting relevant samples and anti-contamination methods) but also identified that there are no clear interpretation standards in many areas of the forensic sciences (Tully 2015). This lack of clarity has led to a gap developing between the interpreted results of experts and how the court reacts to these methods – particularly where the results cannot be statistically represented (Tully 2015). Lastly, the 2015 report published by the Government Chief Scientific Advisor (GCSA) stated that although there have been a range of new capabilities to analyse data, these capabilities may have outpaced a scientist's ability to actually interpret the results (Walport *et al.* 2015, 6). This is to say that although the ability to identify very small trace elements exist, there needs to be a better understanding of the overall forensic significance, along with the need for a better way to communicate different levels of confidence associated with that (Walport *et al.* 2015, 6). A clear conclusion of all the cases and research discussed above is that there still remains a need within the field of forensic science for empirical experimentation, which not only leads to more standard protocols as practices/methods are thoroughly tested but also provides a more in-depth understanding of what the data results are actually representing in certain situations.

### 2.1.5 Quantitative methods development in forensic science

In order to address the concern associated with the lack of empirical data being produced and relied upon within the field of forensic science (Saks and Koehler 2005; Mnookin *et al.* 2011; Morgan *et al.* 2009; Morgan and Bull 2007), conscious efforts have been made in order to address this gap in the knowledge base. Quantitative methods are often employed as they are more likely to be unbiased in nature, focusing primarily on the numerical data that is produced and not the personal biases of the researchers examining that data set. This move towards more quantitative methods is not without its problems, however. One such challenge is that many areas within forensic science (finger-print analysis, blood pattern analysis, bite mark analysis, etc.) are not based on strong statistically based science, unlike forensic DNA analysis (Saks and Koehler 2005). DNA genotyping already had a strong statistical science background, was heavily peer reviewed, and had many validity tests associated with the associated quantitative methods used in analysis before it was applied to forensic evidence analysis (Saks and Koehler 2005). To address the challenge associated with disciplines that do not have strong scientifically based research to base forensic evidence interpretations, the need for more experiments that develop quantitative methods associated evidence analysis has already been stressed numerous times (PCAST 2016; Mnookin *et al.* 2011; Edwards 2010; NAS 2009).

The second of the challenges associated with moving towards more quantitative method development is that all forensic scenes are individualistic in nature (Morgan *et al.* 2009; Morgan *et al.* 2008; Tully 2015). This means that a quantitative method needs to not only address all the aspects that may occur on a specific forensic scene but also all others individual scenes as well. This challenge can be addressed through the use of both primary and secondary experiments (Morgan *et al.* 2009). When conducting early primary experimentation, a quantitative method can be developed which can be easily applied to a range of simple situations and with a focus on level I within the hierarchy of propositions. For example, in Morgan *et al.* 2009, the spatial spread of pollen from cut flowers within an enclosed space was examined but the focus was very limited to a few variables. It was these few variables that formed the bases around which a quantitative method was developed (Morgan *et al.* 2009). When the secondary experiments are conducted which add complexity and individuality to the experiments (Morgan and Bull 2007; Morgan *et al.* 2014), the quantitative methods can then be tested to see if the

analysis of the data is still reliable in more individualistic forensic situations. This allows for the evidence assessments at the level II of the hierarchy of propositions. For example, work undertaken in Morgan *et al.* (2014) expanded on primary experimental work (Morgan 2009) that examined the spatial spread of pollen from cut flowers. In these secondary experiments the time frame was increased and a different location employed (while keeping the quantitative methodology constant) to observe how the spatial spread may be affected and impacted by the added complex and individuality presented (Morgan *et al.* 2014).

The third challenge is that many academic institutes, laboratories and other forensic testing agencies have their own standards when it comes to testing and analyzing evidence (Budowle *et al.* 2009; Butler 2016). For example, in the United States, forensic laboratories are accredited based on general guidelines outlined in the standards put forth by the International Standards ISO/IEC 17025, but are not on more discipline specific guidelines (Butler 2016). Previously this meant that in most instances, personal experience was heavily relied on to interpret the forensic evidence, instead of more scientifically accepted quantitative methods (PCAST 2016; NAS 2009). Once again, the need for more empirical experimentation that relies on a quantitative methodology to analyze the data would address this challenge by building up methods that could be universally accepted (PCAST 2016; Mnookin *et al.* 2011; Edwards 2010; NAS 2009).

In investigating explosive evidence within a forensic context, certain quantitative methods have traditionally been applied. These methods are tied to the strong statistical science behind the chemical components of the explosives. The examination of the post-blast chemical is a common area of study (Hutchinson *et al.* 2008; Bors and Goodpaster 2017). Since these experiments focus on the chemical components found on a forensic scene associated with the explosion, they rely heavily on previously developed quantitative methods. This is similar to how DNA evidence is analyzed in forensic science, which relies on practices and protocols that were developed outside the legal framework. However, in other non-chemical areas of explosive research, more experiments are needed that produce data which can be analyzed in a quantitative manner to form a database that can be applied by practitioners. An example of this can be found in forensic anthropology which is a field that struggled in the past with its lack of quantitative methodology (Dirkmaat *et al.* 2008). One area which has seen improvement is the development of the Forensic Anthropology Database which contain modern

forensic skeletal collections that contain a range of identification criteria gathered (age, sex, medical history, etc.) (Dirkmaat *et al.* 2008). This is just one example of a database (one that is focused on level I of the hierarchy of propositions) that is working on improving the information available to practitioners which provides a large enough sample of modern population markers that can be quantitatively studied and those results applied to current forensic investigation (Dirkmaat *et al.* 2008). No such database exists in forensic anthropology examining the outcomes of explosions.

### **2.1.6 Current research aims and how they will speak to these challenges**

This research aims to address many of the problems addressed in the previous sections (2.1.2; 2.1.3; 2.1.4; 2.1.5) in a particular area of forensic science. It does this by aiming to advance the understanding of the likely distribution of biological debris following an explosive event. As recommended by Morgan *et al.* (2009) this research seeks to use carefully planned primary experiments to look towards understanding the general nature of particular elements under specific situations. Here the forensic elements are the biological debris and the specific situation is a single-source explosive event. This theme runs through the entire thesis, in the hope that concentrating on developing evidence on a specific topic will lead to advancements in the evidence base associated with this forensic issue. In dealing with complexity, the experiments begin with simple conceptions of ‘explosions’ which do not speak to variations in conditions. Hence, a number of experiments have been developed that will examine the simplest of situations in an attempt to begin to build an empirical evidence base. It would be ambitious to expect the experimental element to move on to secondary experiments to examine more complex elements as recommended by Morgan and Bull (2007) in later states of forensic experimentation. If possible, these would focus on understanding the variation of tissue debris distributions in specific contexts – such as any systematic differences in distributions caused by different types of explosive material (e.g. homemade versus military grade materials). This, for example, could then aid investigators in identifying what type of explosive was employed. This is therefore not a main focus of this thesis but contextual variation will be discussed throughout.

An important objective is to develop a clearly communicable and replicable method for producing the forensic evidence base in this instance. The developed

experiments use accepted forensic archeologically methods (see 2.3.1) and the overall methodology is clearly listed to make sure that the resulting experiments can be replicated. This replication of results is one of extreme importance as it helps to validate the original results and provide a more in-depth perspective to the data analyses (Morrison 2014; Michaud *et al.* 2012). To speak to this, much of the methodological development focuses on producing an experimental procedure that enables repeated trials to be undertaken to populate the evidence base. This is done by examining the effect of replacing biological test subjects with artificial ones (gelatine) and by downscaling the experiments in physical size to make the explosions more manageable and cost effective. Whilst acknowledging that the real world is difficult to replicate in such experiments, this should increase validity of forensic science of this nature (Mnookin 2011) and enable the accumulation of knowledge through more extensive experimentation.

In addition to experimentally extensive academic research, professional experience has been used in the development of the experimental method in an attempt to make sure that the research being conducted will have a positive impact in the professional world. An experiment can be well developed and analysed but if the end results will not actually assist the practitioners in the field then why even continue with the research? The distribution of tissue debris mapped from different conditions will ultimately need to be useful and interpretable in practice (Morgan and Bull 2007; Cook *et al.* 1998). For example, maps showing the ‘typical’ distribution of tissue debris following an explosion will be developed in a way that is useful in a practical setting in aiding the initial search and recovery effort. The views of the users will therefore be sought throughout to ensure that relevant goals can be met (Ludwig and Fraser 2014). With a combination of both academic and professional experience, it is hoped that this research will develop a method that can be applied in the field, one that is supported by an evidence base.

A developing field in the forensic sciences is the use of appropriate and reliable statistical techniques in appraising the evidence gathered at a crime scene. The methods that have been developed, while still in their infancy, can be useful in adding both consistency and objectivity in the way in which forensic evidence is interpreted by scientists and practitioners. Some recent examples include work looking into blood pattern produced under different exhalation mechanisms (Geoghegan *et al.* 2017) and looking into using bacterial DNA to identify different soil types (Habtom *et al.* 2017). In

order to aid interpretation in forensic evidence from explosive events, this thesis aims to find appropriate statistics to describe the distribution of evidence and explore similarities and differences across scenes. These chosen statistical methods are discussed in greater detail in Chapter Four.

Finally, to put the research in its forensic science context, it is useful to consider where it might fit into the forensic process. As outlined above, the ultimate goal of forensic science is to explain, reconstruct or predict evidence (Morgan and Bull 2007). In terms of assisting at the scene of an explosion, the aim is to advise practitioners in determining the extent of their search for evidence (i.e. to determine a recommended physical range for searching). To assist with the second stage of analysis (collection and processing of evidence) this thesis explores existing methods for collection evidence post explosion used in forensic archaeology (e.g. the Waldron Springs Protocol, see section 2.3.1) and assesses their use in this context. To contribute to the interpretation stage, the aim is to produce an evidence base that describes a 'typical distribution' in terms of explosive tissue debris and where it may be possible to discuss features that might cause variation from this. To contribute to the presentation stage, the aim is to develop a standard methodology for depicting debris distribution from explosions and a statistical method for comparing them, in an easily accessible and unbiased way for general audiences.

This section has laid down the conceptual framework for this thesis in terms of where it fits into practice of forensic science and also in terms of the challenges posed by conducting a range of experimental studies that are likely to be faced in the course of this research. The experimental approach has been designed to address some of these experimental challenges to ensure that the research is able to progress understanding in the particular field. The following sections of this literature review focuses more on the specific context of the research and explains the need for further understanding in several aspects associated with this PhD research. The use of explosives in terrorism around the world and how this has impacted the field of forensic science is discussed first. The next section introduces the procedures used in forensic archaeology and how it is applied to forensic scene reconstruction. Following this, a background on the current understanding on the nature and dynamic of explosive events is discussed. Lastly, a range of topics associated with explosive research is discussed, including the physical trauma that is created by an explosive event, the use of animals and gelatine models within both



forensic and explosive research, and how scaling has been applied to a range of aspects within the field of explosive research.

## **2.2 The rise of terrorism and its implications for forensic science**

### **2.2.1 A background into the rise of terrorism and the use of explosives**

The use of bombing to achieve the goals of international terrorism, to inflict maximum or mass casualties, has been employed increasingly in the modern era because a bomb is still one of the most effective means of achieving these aims. Conventional bombs remain one of the most likely weapons terrorists use to inflict mass casualties; indeed 88% of the recorded terrorist attacks between 1991 and 2000 involved explosions, which is significant given that some estimates show that terrorist bombings have risen four times between 1999 and 2006 (Quillen 2002, 279; Arnold *et al.* 2004, 263; Morley and Leslie 2006, 6, Wolf *et al.* 2009, 405). Research undertaken into a specific type of terrorist bombing, suicide bombing, found that between 1980 to 2003 this form of terrorist attack was the deadliest form of terrorism used internationally (Hicks *et al.* 2011). This type of attack is often used within a guerrilla war environment. An examples of this can be seen in the attacks carried out by the Tamil Tigers of Tamil Eelam (LTTE), who were one of the only groups (up to the attack on the U.S.S Cole) to use explosive laden boats (Quillen 2002, 282). Another example was observed during the Lebanese Civil War in the 1980's where suicide bombings resulted in over a 1,000 casualties (Quillen 2002). Suicide bombings are often more routinely associated with terrorist groups; examples range from Hezbollah and the attack on the U.S embassy in 1983 to al-Qaeda with their attack on 9/11, along with the more recent attacks like the 2017 Manchester concert bombing or the May 2017 truck bombing in Kabul Afghanistan (Asal and Rethemeyer 2008; Quillen 2002; Morely and Leslie 2006; BBC News 2017; Mashal, Abed, and Sukhanyar, 2017). However it is important to acknowledge that variability exists.

### **2.2.2 The variability that exists within terrorist attacks and the implications for forensic investigations**

Although explosive events are an often used tool of terrorism, there is a range of variability that exists; in fact most attacks will differ from one another (Asal and Rethemeyer 2008; Quillen 2002; Morely and Leslie 2006). This variability ranges not only in the way the bomb is constructed but also in the way it is delivered to the site of the attack and the amount of explosive material that is employed. These variables are often caused by the individual creating the devices, what types of materials that they can obtain to build the bomb, and how they deliver the device. State-sponsored terrorists, like Hezbollah which is part sponsored by Iran, or al-Qaeda which for a long period was supported by the Afghan government, tend to be better trained and supported which means that they have access to more military based materials and, have the understanding to use vastly different bomb materials and methods of delivery (Quillen 2002; Morely and Leslie 2006; Asal and Rethemeyer 2008). In the case of al-Qaeda and the attack on 9/11, they had the funding to gain experience on how to fly airplanes while living in the U.S., which they then turned into a method to commit multiple suicide attacks. On the opposite end of the spectrum, there are those who are not sponsored by any large organization and therefore are not as well equipped or trained. Individuals who fall into this category are often called 'lone actor', with Ted Kaczynski in the United States being a famous example (Gill *et al.* 2014). In addition to a 'lone actor', a group of individuals who operate independently of an organization, though not an overarching ideology are considered 'isolated dyads' (Gill *et al.* 2014, Gill 2012). An example of this can be observed in the case of 7/7 bombers who were a small group without any known ties to terrorist groups and self-financed; as such, they employed inexpensive homemade peroxide based bombs and used public transport to deliver the devices (Quillen 2002; Arnold *et al.* 2004; Kirby 2007; House of Commons 2006).

This variability that exists within terrorist attacks means that when investigators approach a scene to investigate it, there are always unknown factors. For example, have the attacks been conducted by suicide bombers like the 7/7 attackers, or are the terrorists still active and possibly plotting secondary attacks on first responders or at a later date? An example of the latter are the Boston Marathon bombers who placed the backpack bombs at the scene and who were not caught until four days later by authorities after a series of fire fights with police and federal authorities (House of Commons 2006; MEMA

2014). Were the bombs constructed with military grade explosive and therefore the casualties resulting from the attack may have been greater (Morley and Leslie 2006)? Or was the device comprised of homemade explosives which may have been made in a manner that would create fewer casualties due to lack of explosive power (Marshall and Oxley 2009)? Has the bomb been in a backpack or directly strapped to an individual? Or built with the addition of fragmentation accelerators included (i.e. bombs containing nails or other forms of fragmentation) and how large was it? All of these variables and more will result in a different forensic scene and in turn, how investigations will be conducted.

These forensic footprints of a post-explosive scene can contain very important information, not just about the nature of the attacks but also about who the attacker may have been, who may have funded the attack, how the attackers obtained their materials and more. As noted above, the 7/7 bombers used homemade peroxide based explosives. With this information about the bomb type, investigators could work backwards to where they bought the materials to make the bombs, where they gained the information on how to construct the bombs and how they funded their operation. This informed investigators that this group was not tied to a larger terror plot but acted on their own (House of Commons 2006). To the author's knowledge to date there is no systematic evidence base for recording the spatial distribution of the tissue fragments created during an explosive event along with details concerning the specific nature of those events. A few research experiments have been conducted that focus on explosives associated with parameters specific to a terrorism context which focus on the chemical particle distribution and both of which are described in greater detail in section 2.3.1 (Abdul-Karim *et al.* 2013; Abdul-Karim *et al.* 2016). However, the research is still sparse enough that there is a lack of a solid knowledge base from which practitioners can draw on. It is worth noting that there are databases devoted to a range of industrial accidents, some of which involve explosions, but none with a pure forensic science focus (Krausmann *et al.* 2011; Cozzani *et al.* 2010; Nivolianitou *et al.* 2006). With the importance of a solid evidence base having been established in the 2009 NAS and the 2015 GCSA reports, forensic science is slowly starting to focus on this aspect within the field of explosions. This is a gap in the literature that this thesis hopes to begin to fill by contributing to the slowly growing field of information.

## **2.3 The use of forensic archaeology and current forensic investigation**

During a forensic investigation, it is important that the tools employed to locate, collect and record the evidence are employed in a systematic manner. This is critical to ensuring that any forensic evidence located at the scene is properly marked and recorded continuously throughout the on-scene investigation. If the scene is not properly (or thoroughly) investigated, this could negatively impact any court cases that may follow, and possible inclusion/exclusion of evidence. In the case of an explosive scene investigation the need to identify and prosecute those involved is of the utmost importance. Therefore, there is a need to employ a search and recovery method that can be quickly established to deal with the chaos. In employing the methods developed in forensic archaeology, these issues can be addressed in a comprehensive manner and are examined in detail below. Forensic archaeology is when archaeological search and recovery techniques are applied to a forensic context (Hunter *et al.* 1996; Sigler-Eisenberg, 1985; Cox and Hunter, 2005). The techniques that have been developed within the field of archaeology are used to create an accurate representation of the site. Much like a crime scene, once an object has been removed from an historical site any context that was once present is destroyed. By applying a range of techniques, a site can be quickly surveyed and recorded. This allows for any objects location to be recorded in-situ, which can be used later on when the site has been destroyed as a visual representation of the site prior to the excavation. This is how forensic archaeology is applied within a forensic context, in aiding not only the search and recovery process but also in the documentation of the overall site.

### **2.3.1 The forensic investigation following an explosive event**

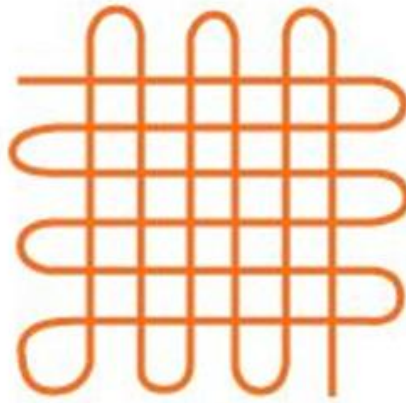
In the immediate aftermath of any explosive event, the area will be very chaotic as the large volume of gases released at a high velocity will produce extreme damage, injury and death (Vermette 2012, 80). The on-scene investigation follows the first stage of the forensic process, trying to identify what to examine/collect and how that evidence can help to identify the three main objects: the target(s), the victim(s), and the design of the explosive device (Morgan and Bull 2007; Cook *et al.* 1998; Vermette 2012, 80). There are also the challenges of dealing with the many problems that arise in the immediate aftermath. These include but are not limited to the continued threat to human safety and

obstacles to protecting the crime scene (Vermette 2012, 87). Common search patterns are often employed at the scene to locate both remains of the explosives material and the victims; however the attempts of first responders to rescue survivors can often disturb the forensic scene (Vermette 2012, 112; personal communication by Brandy Parker 2012).

As discussed above, forensic archaeology is a sub-discipline of forensic science that is designed to deal with the chaos and uncertainty associated with outdoor forensic scenes. In forensic archaeology, the ability to quickly and efficiently search an area to locate and identify interest points is a critical part of the search and recovery process. Several of the steps that are employed within a forensic archaeology investigation are used within this project; one is a visual foot search, with the different types described in greater detail in Figure 2.3 A-C (Durpas *et al.* 2006, 25 - 27).



**Figure 2.3A.** The first is the strip or line search, which when used correctly can provide 100 percent coverage of a site. This search is implemented by having the searchers line up in a straight line and positioned close enough to each other that each field of search vision overlaps. Depending on the search area and the size of the search team, when the searchers complete one line of the search area they will then search in the opposite direction.



**Figure 2.3B.** The second type of search technique is a grid search, which is more time consuming than a more traditional line search as it provides 200 percent coverage of the search area. When a line search pattern is completed, the search team will search the same area, but in a perpendicular direction. This means the search area is searched from two directions and multiple angles, allowing for evidence that is difficult to spot from one direction a better chance of being seen from another direction.



**Figure 2.3C.** The third and last type of search technique is a circular pattern. This type of search pattern works best when the search area and the search team are small or if the search area starts at the top of a hill. This method is conducted from outside to inside, thus preventing evidence from being accidentally stepped on.

Within the search process, the ability to record and process evidence in a quick and efficient method is also important. A way to achieve this, a process that has been adapted for this thesis, is the use of the Waldron Springs Protocols, which employs a set of protocols that reduce processing time for evidence and increases the detection and recovery rates of evidence (Dirkmaat *et al.* 2012, 2-3). This is achieved through the use of the following four separate steps.

1. An intensive and thorough ground search is undertaken which includes the marking of physical evidence
2. A total station is used to collect a three-dimensional spatial map and assign a field specimen number to the evidence (see Figure 2.4 for an example of a total station). It is an electronic instrument that is employed usually in building construction, and records the spatial location of a point or object.
3. Photographs of the evidence are taken and linked with the related field specimen number.
4. The physical evidence, using the field specimen number, is collected, preserved and removed from the scene.

One key aspect of any of the search and recovery techniques employed on these types of forensic scenes is the setting up of a search area that has a high probability of including all of the evidence. To achieve this aim, an understanding of the overall spatial distribution of the forensic evidence is needed, in the case of this thesis; this is the distribution of post-explosion biological matter.



**Figure 2.4.** A photograph of a total station that was taken during the MSc experiments.

The spatial distribution of the chemical components of an explosion has been explored, with one example observed in the research conducted by Kelleher (2002). This research examined the mathematical formulas and the physical principles involved in this aspect of explosive study (see Figure 2.5). Kelleher (2002) states that the explosive particles not associated with the spread of fragments will be limited to a 60 m search radius, regardless of the explosive charge size but not including the effects of wind. The author concluded that the explosive residue originates from a thin outer layer of the charge and that the distribution decreases as the charge size and velocity of the detonation increases.

$$R_{max} = 190p^{-.112}w + 52p^{.858}$$

**Figure 2.5.** Mathematical formula outlined in Kelleher (2002) and developed by Bishop (1958). This formula was developed to identify the maximum distance of the explosive residue will be obtained. In this equation  $R_{max}$  = maximum distance,  $w$  = maximum fragment weight and  $p$  = fragment density (grams per cubic centimeter).

In research conducted by Abdul-Karim *et al.* (2013), the spatial distribution of polymer bonded explosive (PBX) consisting of 80% RDX (research department explosives) was tested both in terms of the distance of the partial spread and the difference of explosive height spread. The findings demonstrated that the recoverable sample of the chemical particles decreased as the distance from the center of the explosive increased, indicating that more particles are located at or underneath the explosive center; this suggest that efforts in recovering this type of evidence from a scene should focus closer to the center of the explosion (Abdul-Karim *et al.* 2013, 3- 5). The 60 meter search radius that was described in Kelleher (2002) was not observed in this experiment as at the 3 m mark the sample size recovered was in parts-per-million (Abdul-Karim *et. al.* 2013, 6).

This research into the resulting post-blast spatial distribution of the explosive chemical residue has continued, with research conducted by Abdul-Karim *et al.* (2016). This research examined using both RDX and aluminised ammonium nitrate controlled explosions to identify the overall spatial distribution patterns (Abdul-Karim *et. al.* 2016, 204). From these experiments it was observed that the post-blast chemical residue mass



can be distributed according to an approximate inverse-square law model. It also highlighted that this distribution trend can vary depending on individual chemical substances (Abdul-Karim *et al.* 2016, 207). Lastly, this research highlighted the impact that weather, in the case of this research the wind direction, has on the resulting spatial patterns to varying degrees (Abdul-Karim *et al.* 2016, 211-212). The resulting chemical distribution was highly impacted by the direction of wind and is an observation that was recorded during the PhD experimentation.

Although the study discussed above follows many of the forensic guidelines discussed in previous sections of this chapter and has an exceptionally strong experimental design, this study focused on the chemical distribution of the explosive material in its own right. This research did not examine what happens to the tissue fragments that are affected by the explosive forces and the resulting distribution of the debris, but rather what happens to the chemical component that makes up the explosive material. Although an important part of any forensic investigation following an explosive event, it is therefore a very different aspect of the overall investigation. The chemicals of the explosives and the tissue fragment created by the explosive forces are impacted by very different variables. The research conducted during the course of this PhD will focus on the tissue fragment distribution and not on the chemical distribution.

During the process of a forensic investigation following an explosion, it is important to employ a search and recovery method that not only helps to deal with the chaos and uncertainty following these events but also one that establishes a proper containment area that includes all the forensically important items. The use of various forensic archaeology techniques and an understanding of spatial distribution of some of the variables that are associated with explosive events can help to achieve this aim. This thesis therefore applies these techniques to the specific area of looking at biological debris from an explosive event and explores the advantages and disadvantages of these processes.

### **2.3.2 Current uses of forensic scene reconstruction**

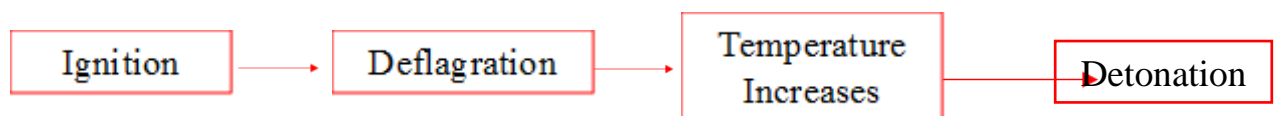
There is a marked similarity between a forensic scene and an archeological site; when either is fully uncovered and investigated, the original 'site' has been destroyed. Once an item is removed from the scene, it can never be placed directly back in its

original location. This is an obstacle to obtaining an understanding of what truly occurred at the site, since if the items in both cases are not documented in a meticulous manner then this vital information is lost. By using a form of forensic scene reconstruction, the location of evidence within a scene can be documented. This spatial information can then play a role in understanding what may have happened at that scene. An example of this can be observed in employing the use of trigonometric reconstruction to identify the location of a blood source through recording of blood impact stains on both vertical and horizontal surface (Raymond *et al.* 1996, 162). The ability to record a complete scene has become an easier task as technology has advanced and digital methods of recording spatial data have become less expensive. The use of 3D digitizing systems can be employed to digitalize the location points of evidence and be used to create a three dimensional model of the whole crime scene (Buck *et al.* 2013, 75; Se and Jasiobedzki 2005). Through the use of forensic scene reconstruction, investigators are able to revisit and examine the scene as a whole at a future date, which allows for multiple examinations of the same data. Forensic scene reconstruction is a useful tool with origins in forensic archaeology (and archaeology generally) and an important aspect of the experiments described within this thesis. A total station will be used to do the spatial data collection necessary for whole scene reconstruction (discussed in greater depth in section 4). To summarize, it appears that forensic archaeological approaches show promise in analyzing the post-explosive distribution of biological material. This thesis will therefore employ the Waldron Springs Protocol for searching, and the total station approach for recording of findings. The appropriateness and usefulness of these techniques in the experiments described will be discussed in the thesis conclusions.

## **2.4 The explosive process**

To fully understand the aftermath of an explosive event, an understanding of how an explosion actually takes place is required. This is important in order to have a full understanding of why forensic scenes involving explosives look the way they do and therefore enables the first steps in the forensic process to be appropriately undertaken (2.1.1). The explosive event can be divided into four stages which are (see Figure 2.6 for a visual illustration):

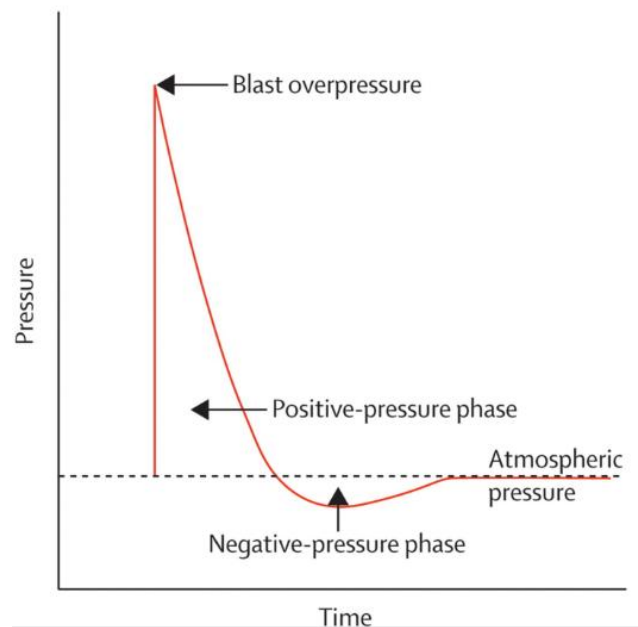
1. An explosion begins with the ignition stage which occurs when part of an explosive material is heated to or above its ignition temperature (the minimum temperature required for the process to begin) (Akhavan 2004, 63). This process starts with an external stimulus being projected into the explosive material, which increases its internal temperature and creates the chemical changes needed for the explosion to occur. These chemical changes in the explosive material are necessary for the explosive event to begin (Akhavan 2004, 63-64).
2. The next stage is deflagration and occurs when the explosive material burns.
3. During the third step, the temperature of the chemical burning continues to increase.
4. The fourth step is the propagation of the detonation and occurs when the chemical material reaches the temperature at which it explodes (Akhavan 2004, 64). ???



**Figure 2.6.** A visual depiction of the explosive process

The blast wave resulting from an explosion is at the heart of this research, and as such having a comprehensive understanding of the basic principles therein is vital to explaining the resulting tissue fragmentation and spatial spread. This blast wave is created after the explosive has detonated, which is created by the shock wave moving through the explosive material. The propagation of the detonation blast wave is itself an extremely complicated process, but it acts in a similar manner to a sound wave with both regions of rarefactions and compressions (Akhavan 2004, 54; Baker 1973; Carr 2016; see Figure 2.6 above). In order for the blast wave to move in a forward direction, the high pressure in the shock front (which is created by a temperature difference between the regions of rarefactions and compressions or exothermic decomposition) needs to move forward to a region of lower pressure (Akhavan 2004, 55; Akhavan 2004, 100; Edwards and Clasper 2016). Once the shock wave has achieved a steady state (when the chemical reaction equals both the energy lost to the surrounding medium as heat, along with the loss of the energy used to compress and displace the explosive crystals), it reaches supersonic speed

and creates the explosive detonation of the material (Akhavan 2004, 56; Born 2005, 280; Edwards and Clasper 2016). Once the detonation has occurred, the blast wave begins to move out from the center of the blast and instantaneously causes increases in the surrounding pressure (see Figure 2.7 below). As it moves further away, the environmental pressure decreases to below that of the ambient air pressure and an acoustic wave is created, which drags debris into previously unaffected areas. Not all explosive events take place in a wide-open space and there are many cases in which the blast wave hits a structure or surface and is reflected back on itself. The refracted blast waves can often travel at speeds and angles (creating an irregular refraction or mach stem) that exceed those of the p



**Figure 2.7.** A diagram depicting the blast pressure and pressure time curve (Wolf *et al.* 2009).

As discussed earlier (2.2.2), one explosion will differ from another if there are variations involved. Even if the same type of explosive material is used, the placement of the charge can impact the initial direction of the explosive process and therefore the resulting blast wave direction. For example, the shape of the explosive material will impact the direction of the shock wave as it moves through the material and the resulting blast wave direction. Different environments, for example indoor in contrast to outdoor, will greatly impact the range and distribution of the damage caused by the explosion. As observed during the 7/7 bombings, injuries were more severe in the tube carriages as the resulting blast wave was able to bounce off the sides of the carriage and the tunnel (House

of Commons 2006). This would increase the distance the wave was able to travel, but by refracting back onto itself adding to the energy present within the blast wave. The placement of the device in relation to the target or targets will also produces differences in the damage that is caused by the explosive event. The examples above are just two of the many external variables that can create an even more complex and varying end result. In an experimental setting, a way to deal with the variability that can exist in these situations is to run multiple tests that observe explosions with controlled variables (placement of the charge, stable environment, etc.) and without the addition of external variables (different environments, changes to explosive content, etc.). In the creation of experiments that examine the simplest situation we can establish the base line situation to which more complex situations can later be compared (Morgan *et al.* 2014; Morgan *et al.* 2009). Therefore, this thesis aims to establish a baseline for understanding the distribution of biological material following an explosion as a central objective.

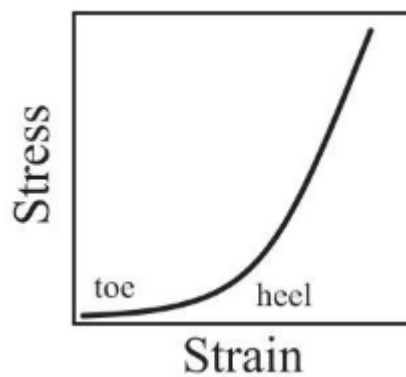
## **2.5 Relevant explosive research**

This section examines research that has investigated trauma caused by explosive forces on biological tissue. This section is relevant to obtaining further information necessary for designing experiments which aim to emulate the type of trauma that would be caused to a live body caught in an explosive event. The extent to which the experimental method chosen achieves this aim will be discussed later in the thesis conclusions.

### **2.5.1 The current understanding of the physical trauma associated with exposure to explosive forces**

In order to understand why a forensic bomb scene looks like it does, it is important to first understand the basic underlying mechanical principles of the bodies of individuals involved in the attack and how they react to the resulting explosives forces. In this instance it is the forces of stress and strain that combine to result in a number of different types of observed injuries. The concept of stress can be explained as a force that pushes or pulls on an object and is measured in the average force per area of application (Huston 2009; Kieser *et al.* 2012). There are two basic principles that are associated with

the concept of stress: positive tensile stresses and negative compressive stresses (Currey 2002). Strain, on the other hand, can be explained as the changes in length in a particular direction; normal strain which is proportional changes in length, engineering strain which is the change in length in particular direction, and shear strain which is a change in the angle undergone by two lines originally at a right angle (Huston 2009; Currey 2002; Kieser *et al.* 2012). The stress- strain curve is a model created to show how an object responds to a given load and can be used to identify the maximum amount of stress that an object can handle or the ‘ultimate stress’ of an object (Cullinane and Salisbury 2005). The stress- strain curve, shown in Figure 2.8 below, follows the modulus of elasticity (or Young’s modulus) which defines this stress- strain relationship in the linear region of the curve of an ordinary tensile or compression test (Currey 2002; Kieser *et al.* 2012).



**Figure 2.8.** A graph demonstrating the typical stress-strain curve of biological tissues. The areas labelled toe and heel do not refer to the biological body parts but to a region of low modulus (toe) that curves around to give way to a region of higher modulus (heel) (Vincent 2012, 50).

The physical trauma observed at the scene of an explosion is directly related to the rapid radial expansion of the shock wave created by the explosive process (Kitulwatte and Pollanen 2012, 742). When applying the stress-strain relationship discussed above to what the body undergoes when exposed to the blast wave, failure of the biological structures happens immediately creating the observed fragmentation of said tissue. For example applied shear stress can result in the tearing of tissue (Carr 2016, 262). However, this failure rate will differ between tissue types, along with differing between soft and hard tissue. As a rule with explosive injuries, the closer to the centre of the explosive event, the greater the explosive energy an individual is exposed to. There are four distinct

categories of explosive injuries which are detailed in Table 2.1 (Kitulwatte and Pollanen 2012, 742).

Type of Injury	Description
Primary Blast Injuries	Caused by a sudden change in the surrounding environmental pressure and associated with those in direct position to the blast centre (Leibivici <i>et al.</i> 1996; Ramasamy <i>et al.</i> , 2011).
Secondary Blast Injuries	Caused by those objects energized by the explosion that become projectiles (Covey 2002, 1221; Ramasamy <i>et al.</i> , 2011).
Tertiary Blast Injuries	Injuries caused as a result of a structure failure (e.g., building collapse) (Covey 2002, 1221; Ramasamy <i>et al.</i> , 2011).
Miscellaneous Blast Injuries	Caused by exposure to dust, thermal burns or burns caused by the blast (Covey 2002, 1221; Ramasamy <i>et al.</i> , 2011).

**Table 2.1.** A collective list of the four main types of injuries caused by the exposure to an explosive event

The many different categories of injuries associated with an explosion range in severity, distribution and patterns. First, an explosive force decreases rapidly as it expands outwards and to be severely injured by the blast forces, an individual needs to be located near the source of the explosion (Marshall 1988, 66). Second, explosive forces are also directional in nature and the direction of the blast is directly connected to the types of injuries observed in victims (Marshall 1988, 66). Third, explosions that occur in an open space demonstrate very different injury patterns on individuals affected by the event (enclosed spaces produce more primary blast injuries, burns, overall injuries and ultimately, higher death rate events (Leibivici *et al.* 1996)). Finally, clothing worn by an individual can act as a form of protection to the skin from some of the fire exposure that can result in the explosive event (Eckert 1981, 352).

When an individual is caught in the path of a blast wave, they can experience an increase of eight times the local environmental pressure (Covey 2002, 1222). Initially when the blast wave hits the human body it is in a directional nature which means that the wave will strike one part of the body causing it to compress locally, spreading to a more

general compression as the blast wave completely envelopes the body (Proud 2013). This results in a stress wave that travels through the body, creating pressure differences between mediums of different densities within the human body (due to how the different tissue/materials react to stress/strain), resulting in four different types of damage to the living tissue as described in Table 2.2 (Covey 2002, 1222). The subsequent blast wave that is produced in an explosion creates very different observed injury patterns which are explored below in Table 2.3.

Type of Blast Injury Caused by Pressure Changes	Description of Blast Injury (Covey 2002, 1222)	Example of Injury Type
Spalling	Occurs when particles from a more dense fluid are thrown into a less dense fluid and this occurs in regions where these two fluids meet	Present in the lungs as alveolar hemorrhage, which is bleeding in the lungs directly into the alveolar space (Yeh and Schecter, 2012)
Implosion	Occurs when a gas pocket momentarily contracts when the blast wave enters the tissue. As the shockwave leaves the body and the pressure decreases the gas pocket expands rapidly and causes injury from mini internal explosions	Presents in the lungs as an air embolism moving from the alveoli into the pulmonary circulation (Yeh and Schecter, 2012)
Acceleration-deceleration	As the blast wave enters the body, organs are moved as the body wall moves in the direction of the shock wave. Adjacent structures may move at a different rate, causing shearing or a disruption in the tissue	Present in the brain as moderate to severe traumatic brain injury and can often lead to post traumatic stress disorder later on (Elder and Cristian, 2009)
Pressure differentials	Occurs when the blast wave creates a pressure difference between the outer surface and the inner surface of the body, resulting in pressure differential injuries	Can be observed as nonbowel intra-abdominal injury (Wightman and Gladish, 2000)

**Table 2.2.** A description of the types of injuries that can be obtained by the pressure changes observed in an explosion. This demonstrates the extreme power of the explosive force that is produced in the chemical reaction which begins this process.



Injures Associated with the Blast Wave	Description
Blunt Trauma	Trauma that is created by the explosive energies travelling through the body and by non- penetrating projectiles (Proud 2013)
Traumatic limb amputation or flail injuries	Direct result of the blast wave or by debris hitting the limbs and causing the resulting amputation (Kitulwatte and Pollanen 2012, 744; Leibivici 1996; Hull and Copper 1996)

**Table 2.3.** A short description of the types of injuries created by the blast wave forces alone.

Although there is a wealth of knowledge on the trauma that is associated with an explosive event (Kitulwatte and Pollanen 2012; Leibivici 1996; Hull and Copper 1996; Covey 2002; Ramasamy *et al*, 2011; Proud 2013; Marshall 1988), there is a lack of understanding of the spatial distribution of the tissue fragments created by the explosion. This lack of understanding hinders the overall forensic investigation as an understanding of this process would aid in the development of better search areas.

## 2.5.2 The use of animals within forensic sciences

As evidence bases are crucial within forensic science, it is vital to create appropriate data that mimics (as closely as possible) real world situations. Due to limitations placed on using humans cadavers in forensic science experiments, tissue substitutes are often used by researchers. This allows for the forensic experiments to still be conducted and explore many of the situations present in a real world environment. Animal models are very common and range from using rabbits to pigs to test out a range of forensic situations (Turner and Wiltshire 1999; Cattaneo *et al*. 2015; Scholl and Moffatt 2017). Pig cadavers are often chosen for several reasons when looking for tissue materials to conduct experiments. The first is that pig cadavers are easier to obtain and do not have the same ethical and legal restriction placed on their use in research as human cadavers. Pig cadavers have also been shown to be similar enough to human cadavers to provide accurate data results (Schoenly *et al*. 2007; Catts and Goft 1992; Passalacqua and Fenton 2012). Both pig cadavers and human cadavers have similar internal anatomy, fat distribution, chest cavity, omnivorous diets, lack of heavy fur, bone density composition, etc. These factors add up to make pigs a suitable substitute to humans (Schoenly *et al*. 2007; Catts and Goft 1992; Passalacqua and Fenton 2012).

Within forensic decomposition studies, animal models have been widely employed. As decomposition is a complex process that is affected by a range of variables (including: perimortem/postmortem trauma, environmental temperatures and conditions, exposure of cadavers or burial depth, etc.). Animal models, often pigs, are applied to develop an understanding on many factors and how they work together to alter the rate and pattern of decomposition which are important in unraveling important forensic concepts – like PMI (post-mortem interval) (Olakanye *et al.* 2017; Horenstein *et al.* 2012; Catts 1992). The use of pigs as experimental models also extends to studies of trauma. Many factors go into creating trauma on both soft tissue and the bony structures, from the amount of force applied, to the precise time of the trauma (perimortem or postmortem), to the specifics of the weapons themselves. Work done by Martin Fackler (1986;1987;1988;1996) into gunshot ballistic often employed pigs as a human substitute to explore in-depth resulting trauma. Through using animal models – like pigs – it is possible to explore these different variables under strict experimental conditions, and therefore provide an excellent means of identifying the factors behind a trauma injury (Geddes *et al.* 2000; Wang and Ba 2010; Wieberg and Wescott 2008).

There are some negatives to using pigs as substitutes to human cadavers in forensic experimentation and these are primarily due to ethical concerns surrounding the use of animals in medical and scientific studies (Cattaneo *et al.* 2015; Francione 2007; Knight 1992; Pound et al 2004). In the area of medical research, the use of animals in experimentation is general accepted since the results have a direct impact on human medical advancement. In the case of forensic science, the results from the experimentation do not help the living but help the dead. Since the living are not aided, the use of animals in experimentation often falls into a grey area, especially if the experimentation is conducted on animals that are still living (examining perimortem verse postmortem injuries, etc.) (Cattaneo *et al.* 2015; Francione 2007; Knight 1992). That being said, the vast majority of the experimentation that is conducted on animal models in modern forensic science is done on animals that have been dead before the experimentation was conducted, with the death of these animals done in a humane manner and in accordance with animal welfare laws (Cattaneo *et al.* 2015; Francione 2007). It should be noted that although animal cadaver models are widely considered to be a good substitute to human cadavers, recent research that has yet to be published may

raise some questions as to the reliability of employing animals as human substitutes within forensic decomposition experiments (Goode 2016).

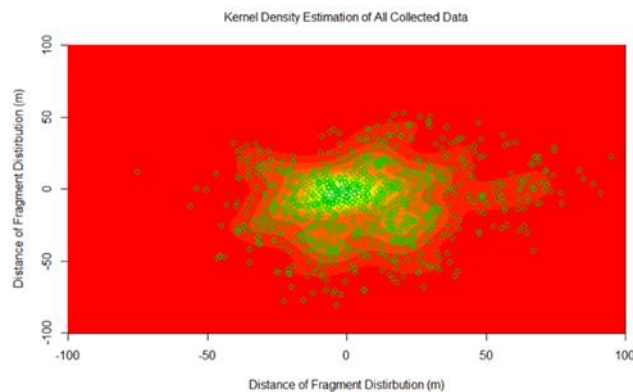
#### **2.5.2.1 Previous experiments using animal models in explosive research**

One example within the area of explosive research using pigs as human proxies is the research conducted by Christensen *et al.* (2012) which examined a series of explosive tests to identify the fracture patterns associated with blast trauma. Eleven pig cadavers were exposed to a series of four explosive tests. This series of four experiments tested a range of explosive type, charge size, distance from the target, along with some test including shrapnel (Christensen *et al.* 2012, 6). The skeletal trauma that was observed within this study was extensive. The observed fractures were complex, in both that they were comminuted with numerous small displaced bone fragments. Other primary blast injuries, like traumatic amputations of limbs and cranium, were also observed throughout the course of these experiments. One of the major outcomes from this study was that the observed fracture patterns were concluded to be unique enough from other types of fracture patterns in other causes of skeletal trauma to be specifically associated with blast trauma (Christensen *et al.* 2012, 9).

##### **2.5.2.1.1 Author's Previous Research conducted during an MRes degree**

The author of this PhD research constructed her first animal model to represent a suicide bomber explosion in 2014 as part of her MRes dissertation (DuBois *et. al.* 2017 and see Appendix A for full details). The premise of this research was that animals could be used to adequately represent these types of events and that new evidence would arise that would be helpful in forensic investigations. The research involved obtaining and preparing nine pig cadavers used to represent human subjects. Large pigs were selected because they have been shown in prior literature to be a good substitute for an adult human (Christensen *et al.* 2012; Schoenly *et al.* 2007; Catts and Goft 1992; Passalacqua and Fenton 2012; Aulick *et. al.* 1981). The author obtained the permission to conduct controlled explosions in the Mendip Hills area in Somerset, UK for the experimental aspect of her Master's project. Alfred Technologies undertook the setup and the controlled explosions for these experiments and the resulting fragmentation distribution

was recorded using a total station as detailed more completely in section 4.1. The pigs were exploded across the course of 4 days and under a range of environmental conditions that were outside of the authors' control. The resulting fragmentation distributions had a number of similarities as well as differences, Figure 2.9 (below) is a replication of all nine explosions together (replicated from DuBois *et al.* 2017 with further details in Appendix A). The majority of the fragmentation was located at or near the blast centre and the overall spread is directional in nature.



**Figure 2.9.** The Kernel Density Plot of the combined large pig tests data rotated and lined up to show the collective spread of the fragmentation. As noted above the majority of the fragments are recorded at/near the blast centre.

The key points from this MRes research was that the mean maximum distance of the fragments was recorded at 76.5 meters and the overall shape of the distributions was highly influenced by the placement of the explosive device. In terms of these findings, similarities were found to real world suicide bombers and the types of trauma that is usually sustained due to the close proximity to the blast centre (Christensen *et al.* 2012; Leibivici *et. al.* 1996; Covey 2002; Ramasamy *et al.* 2011). Traumatic limb amputation and other primary blast injuries like decapitation were the most commonly observed (see Tables 2.1 and 2.3 for further details). The MRes study concluded that the large pig cadavers did appear to be realistic substitutes for human suicide bombers and therefore assisted with the validation of using experimental animal studies to emulate these types of conditions within a forensic context.

One of the many problems that are often associated with conducting experimental forensic research which emulates trauma to the human body, is that there are limitations

to using large animal models (for example pig cadavers) as human substitutes. These animal substitutes are often very expensive to obtain, as future profits associated with the sale of the animal often need to be paid in addition to the original cost. These expenses are often compounded by the difficulty in finding a way to transport and appropriately store these materials. Often the options available to researchers (large cold storage units, cold storage transportation, etc) are very expensive. Another issue with using large animal models in explosive research is that a large amount of explosive is required to produce complete fragmentation of the target (DuBois et al. 2017; Christensen et al. 2012). Explosive materials are difficult to obtain due to restrictions placed on who can buy and use high explosive. Like the expense associated with obtaining large animal models, buying explosives is another high financial cost. Lastly, finding a range/ space in which to safely use high levels of explosive is a further challenge. A large open space is needed to prevent injury to those involved in the experiment and/or structural damage. A professional who can safely handle large amounts of explosives is also required which is another added expense.

In addition to the monetary expense associated with the use of biological tissue, employing biological tissue at an explosive range can also be an issue. Many ranges that do conduct explosive testing do not want biological tissue to be used on their range. This is due to the fact that these ranges often conduct chemical experiments and stakeholders do not want the range to be contaminated for future testing by the biological tissue fragments. A further element to consider is that whilst there are justifiable reasons for conducting animal studies (on dead animals) from an ethical point of view, they are viewed by some as distasteful and sustained use of animals in the production of a reliable evidence base would not be desirable from an environmental perspective (Knight 1992; Cattaneo et al. 2015). These issues only add to the difficulties associated with conducting this type of research. Experiments are important in that they provided a path to test out different ideas and methods that can aid in developing more appropriate methods of best practice (Morgan and Bull 2007, Edwards 2009, Mnookin 2011, Morgan et al. 2009; PCAST 2016; NAS 2009; Tully 2015). Without experiments, practitioners are often left without the necessary information about how to explain, reconstruct or predict evidence.

With few researchers conducting experimental research of this nature, it means that there is a lack of an empirical evidence base. In addition, there continues to be very

limited understanding of what actually occurs in these types of explosive events. With the overarching goal within the field of forensic science to explain, reconstruct or predict evidence (Morgan and Bull 2007), this presents a critical problem. Through using experiments, decisions concerning various methods can be validated and areas where further study needs to be conducted can be identified (Edwards 2009; Mnookin 2011; Morgan et al. 2009; Morgan and Bull 2007; GCSA 2015, PCAST 2016; NAS 2009; Tully 2015). By applying knowledge obtained through experimental studies, evidence that is present at a forensic scene can be handled and interpreted in a manner of best practice (Morgan et al. 2009). With no evidence base in which to rely on to understand the evidence that is collected, practitioners are limited in how they are able to draw conclusion about a forensic scene beyond their personal experiences.

### **2.5.3 The use of gelatine to test impact forces**

Access to biological tissue to test theories associated with impact forces and damage can be difficult to obtain in a forensic setting due to ethical concerns (Cattaneo *et al.* 2015; Francione 2007; Knight 1992), thus hindering the development of an empirical evidence base in which investigators can use through the different stages associated with the forensic process (2.1.1). One material that is often used to address the ethical concern while still conducting this type of important research, like research into bullet lethality (Nicholas and Welsch 2004), is gelatine. Modified gelatine or modified silicone is a thermoreversible material formed from a polypeptide chain dissolved in water (Juliano *et al.* 2006, 2085). It was developed by researchers as an inexpensive way to better understand how impact forces are transmitted through the soft tissue of the body (Juliano *et al.* 2006, 2084; Jussila 2004, 91, Nicholas and Welsch 2004,1). The use of gelatine as a substitute is possible because of the way it simulates the density and viscosity of human tissue (Nicholas and Welsch 2004, 1; Carr *et al.* 2018). This similarity can be seen in how gelatine acts in resistance to forces in a similar manner as living tissue does. Translated, this means that the gelatine can be used to determine the potential tissue damage from the level of damage inflicted on the gel (Lyon, Bir, and Patton 1999, 3). The final gelatin consistency and composition of the gelatine will vary between researchers, but the usual ranges are between a 10% to 20% concentration (Jussila 2004, 91; Carr *et al.* 2018). The gelatine also reacts with known mechanical behaviors to temperature changes in

predictable ways, allowing researchers to study the time and strain dependent mechanical properties associated with tissue using gelatine (Juliano *et al.* 2006, 2085).

Although gelatine is a commonly used substitute for actual tissue in firearms ballistic tests, there are some downsides to its use. The first is that for different researchers, the final consistency and composition will differ (Nicholas and Welsch 2004, 5). This means that although the gelatine material is used widely, the actual material used by different research differs. Another is the importance of using the gelatine soon after making it, as the evaporation of the water from the gelatine alters its mechanical properties (Juliano *et al.* 2006, 2085). Another challenge to using gelatine over natural tissue is based around the constancy of the materials. Gelatine is non-isotropic in nature and there is a certain amount of uniformity present within the tissue (Juliano *et al.* 2006, 2085). Biological tissue is polydisperse and there is a certain amount of differences between different tissue groups (Juliano *et al.* 2006, 2085). This means that when gelatin is prepared correctly they are homogeneous whereas the human body as heterogeneous (Nicholas and Welsch 2004, 5; Carr *et al.* 2018). Even with these limitations, it is nevertheless the closest non- biological substitute to biological tissue. With the large body of literature supporting its use and outlining its compatibility despite the limitations suggests that it is an option worth exploring. In the context of this thesis, the use of gelatine rather than biological tissue is a central theme. In finding products and processes that enable the reproduction of an experiment on multiple occasions and therefore encourages replication, the hope is that this will encourage the production of the kind of evidence base that is often still lacking in a forensic setting (Morgan *et al.* 2009).

#### **2.5.4 The use of scaling within the field of explosive research**

Within the field of explosive research, the use of scaling to conduct experiments is widespread. Working with explosives is not only expensive but can also be dangerous. Using smaller, properly scaled tests is advantageous, as it means that multiple tests can be run within a single day (test-run) which will increase the number of results that can be obtained and studied (Kleine *et al.* 2003, 124). This then allows practitioners to predict the properties of the blast wave of much larger explosions based on testing conducted on smaller amounts of explosives (Baker 1973; Esparza 1986). The use of smaller amounts of explosive reduces the cost of conducting this type of research, which also allows for

more tests to be conducted and to produce more data. There are several methods that allow the results of smaller scaled experiments to be applied to large scale explosions, which have been tested extensively (Kleine *et al.* 2003, 128 - 129; Hargather and Settles 2007, 215). In terms of explosives, it is important for the scaling process to take into account the energy that is released and the strength of the blast wave. One of the most common methods used for scaling explosive is called Hopkinson-Cranz's model (Kleine *et al.* 2003, 128; Hargather and Settles 2007, 215; Esparza, 1986). This scaling law allows for the scaling of mass, distance, and time or based on a cube root law for a wide range of explosive charge sizes (Hargather and Settles 2007, 215). It also assumes that a similar shock wave is produced at a scaled distance from two charges of different mass but of the same explosive material when detonated in the same atmosphere (Hargather and Settles 2007, 219; Kleine *et al.* 2003, 128). This scaling method can be expressed in the formula below in Figure 2.10.

$$\frac{R_1}{R_2} = \left( \frac{W_1}{W_2} \right)^{1/3} = \left( \frac{E_1}{E_2} \right)^{1/3}$$

**Figure 2.10.** The formula for the Hopkinson-Cranz model, in which R represents distance, W represents the charge mass and E represents the amount of energy released by the explosion (Kleine *et al.* 2003, 128).

For this scaling method, a known amount of explosive material can be applied within each formula and through using basic algebra, the new scaled amount of explosives can be determined. It is this new explosive material amount that will then be applied to the testing of downscaled experiments used in this thesis. Although scaling within an explosive based situation has been examined, what makes the experiments that will be conducted in the course of this PhD research unique is that a range of materials are being tested and compared. It should also be noted that these scaling laws have only been applied to explosive amounts and not to biological or none biological tissues. In order to observe how these explosive scaling equations would apply to other aspects of explosive experimentation research more data from scaled experiments is needed. This will provide an observation into how the resulting explosive equation solution compares to what is observed in the field within a scaled experiment with tissue fragments. Due to the reduction in the costs associated with purchasing the materials (both the targets and the explosives amount), both gelatine and biological material in the form of both piglets and large pigs can be examined. It is through the scaling of half of the target materials



that the cost associated is greatly decreased. This allows for more experiments to be conducted and produce more data that can be analyzed.

## **2.6 How the Research Questions address the gaps highlighted within the Literature Review**

The review of the research literature on the challenges of forensic science, the rise of terrorist incidents involving explosions, the opportunities offered by forensic archaeology approaches and the lack of research on the spatial distribution of biological matter post-explosion have motivated a general thesis aim. This general aim is to examine if it is possible to realistically recreate post-explosive forensic scenes with the overarching goal of establishing a workable evidence database. To try and achieve this, the aim was to undertake easily replicable experimental work to build an evidence base, and construct a method for analyzing, the distribution of biological matter in the wake of an explosive event. In this section, this general aim is separated into five specific research questions which inform the structure of the experimental research and the format of this thesis.

### **2.6.1 Can data from scaled experiments be used to develop more evidence- based search and recovery methods?**

In order to address this gap in the empirical evidence in this area of explosive research, one of the main goals of this thesis was to develop a method to open up the field to more researchers. One way of achieving this is to examine if scaling down the size of the experiments, in order to reduce the costs and time involved, produces similar results to experiments conducted using large scale animal models. This aim was achieved by conducting a set of tests where scaled animal models were tested using a similarly scaled amount of high explosives. Experiments were conducted in which five piglets with a scaled amount of explosive was applied. These were compared to data from nine experiments in which full sized pigs had been exploded. Through the use of a program developed in R Studio, the two data sets were compared and contrasted to explore the statistical similarities of the resulting spatial distributions. If the results demonstrated consistency, and scaled experiments appeared viable, then the costs associated with

conducting this type of research could be reduced, thereby opening up the area of research to more researchers. As smaller animals and non-biological materials are often cheaper and easier to obtain, the use of either of these materials could decrease overall experiment cost. This idea will be explored and discussed throughout this thesis.

### **2.6.2 Can gelatine be employed as an alternative tissue target to biological matter in explosive experiments?**

A series of experiments were designed to address this issue within this thesis which focuses on a suitable replacement tissue to using biological tissue. As described in detail in section 2.5.2, gelatine was chosen as it has been applied in forensic research to test out how force is transmitted through the human body (Juliano et al. 2006, 2084; Jussila 2004, 91, Nicholas and Welsch 2004, 1). Two separate experiments were conducted which examined how similar ballistic gel fragments behaved when compared to biological tissue. The first experiment looked at how a large gelatine block compares to the large scale pig experiments. This was an important step in determining if gelatine on a large scale would produce similar results to the large scale pigs. The second experiment then examined if on a scaled level, the gelatine produces similar fragmentation distribution to the scaled piglet targets. The aim of this series of experiments is therefore twofold. The first is to establish if on a large scale the gelatine data is similar to that of the large pig experiments and is therefore a suitable tissue substitute to using biological tissue. The second aim is to examine if the use of gelatine as a suitable tissue substitute would be appropriate on the scaled level as well. If a non-biological target works both on a large scale and scaled level, then this would be ideal from the viewpoint of opening up the possibilities of experimentation to more researchers who could help create a large empirical evidence base for practitioners to draw on.

### **2.6.3 Do tissue fragment experiments with restricted variation present provide enough data that can be reliably applied to real world events?**

To address the issue of how experiments with restricted variables are reliably applied to real world events, data that was collected in the experiments conducted during this PhD thesis were compared to a large scale law enforcement training exercise. This

exercise was designed to recreate a bus explosion and secondary attack on first responders. Those involved in this exercise ranged from the local FBI field office, the police EOD team, the county Medical Examiner's office and the local ATF field office. This was important in understanding if the experiment methodology produces similar enough results to what actually occurs in a closer to real world scenario. If too different, then the experimental procedures would need to change in order to produce results that are more plausible. The more realistic the data results are, the more realistic the methods of best practice that are outlined in the empirical evidence base will be. The chapter that focuses on this real world application will use both data on physical results of the explosions collected from the training scenarios to explore this area of interest in greater depth.

#### **2.6.4 What is the best process for comparing and contrasting the data gathered from each of the different experiments?**

The experiments that are involved in this PhD would be classified as primary experiments that will be used to develop an overall evidence base. This means that the method that was employed to analyze the data was developed over time as more information was gathered that needed to be interpreted. These additional aspects often came with trying to deal with the complexity and variability that existed even in experiments that were already designed to minimize such variation. By using statistical analysis to examine the data collected and to compare the data sets to each other, a more scientifically sound manner of looking at and understand the data was employed. Questions associated with the data, both in the general analysis and in the inter-data comparison could be addressed using a statistical program that was constantly deployed throughout the PhD. In using a statistical method that was constant throughout the research, the validity and reliability of the overall methodology could be assessed. For example, across the experiments that are employing the same methodology how similar are the results to each other? Is keeping the method constant enough to override other factors like environmental pressure (e.g., wind, temperature) on the resulting data or do these outside factors still impact the data enough that these factors need to be accounted for more closely in real world situations? In using a statistical program, the data can be

scientifically study to address these questions which helps in establishing a useful evidence base that can be applied by practitioners.

#### **2.6.5 How valuable do law enforcement practitioners find forensic experimentation and resulting evidence?**

A series of questions were posed to practitioners to examine how they not only viewed forensic experimentation but also how they employed the results from such experiments in their everyday investigations. The first question was aimed to see how relevant the forensic techniques that were being employed during the training exercise were in a real world situation to try and understand if the techniques are actually usefully in a complex, time pressured situation. The second question looked at what types of questions practitioners are normally asked in a court room situation to try and understand how important their personal opinions are in developing an understanding of what occurred at the forensic scene. The next question was designed with the aim to understand what helps the practitioners on the forensic scene to form these personal opinions about what may have occurred on the site. The fourth question examined the strength of the working relationship between the practitioners and forensic science personnel that work with their organization. The next question further examined this aspect by asking the practitioners their views on how well forensic and law enforcement work together on a forensic investigation. The sixth question on the questionnaire looked at if any of the practitioners applied the use of forensic relevant evidence databases when trying to understand what occurred on the scene. The last question asked the practitioners what aspects of the forensic investigation could be improved on or changed to better understand what they view as the important needs are in the current field of forensic science.

#### **2.7 Conclusion**

The above sections have highlighted the importance of an evidence base, replicable experimental methods, and unbiased evidence interpretation in the field of forensic science. Although the range of variability that exists between single explosive events are numerous, the rise in these types of terrorist attacks nevertheless demonstrates

the need for an evidence base that practitioners can readily employ in both evidence collection but also evidence interpretation. Research has started to be conducted into this field and although there are still many gaps with the literature, this thesis aims to try and address these gaps within the knowledge base through the use of reproducible experimentation that can be applied with ease by practitioners and researchers.

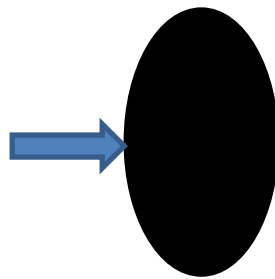
## **Chapter Three. Materials and Methods**

As outlined throughout Chapter Two, the importance of developing a robust evidence base is critical for forensic science (Morgan and Bull 2007; Morgan *et al.* 2009; Cook *et al.* 1998). Through the development and execution of repeatable experimentation, an understanding of the simplest aspects of forensic science can be gained and then built upon to create an evidence base that can be employed by practitioners in the field (Edwards 2010; Edwards 2009; Morgan 2009). This project aims to develop a repeatable realistic experimental methodology that can be used to create the foundation for this by focusing on measuring a single outcome: the spatial distribution of the tissue fragments created during an explosive event. This is an area of explosive research has not been explored in any depth and the unique methodology discussed below was developed to address the numerous challenges associated with examining this new area of study. This chapter sets out to detail how the physical experiments were set up and the resulting data produced collected. The following chapter (Chapter Four) will explore in greater detail how the results of experiments were visualised, described and compared through statistical analysis through the use of a unique program developed in R studio. This latter element addresses research question 3.4.

### **3.1 Experimental set up**

All the field experiments described in this thesis were designed to examine how the tissue from an explosive target distributes spatially. In the experimental tests that were performed over the course of this research, it was important that all variables other than the experimental ones were kept constant to enable result comparison across experiments. The intention was to produce only the simplest and most basic of situations in order to develop a scenario that could form a solid evidence base (Morgan *et al.* 2009). In this research, the same methodology was utilised in all experimental tests; this was to make it easier for others to replicate these experiments and make sure that the results presented are held to high scientific standard (Edwards 2009; Edwards 2010; Morgan *et al.* 2009).

In order to control for key explosive variability factors (shock wave and blast wave direction, etc.), the placement of the primer charges was kept constant and always placed in the same location directly onto the side of the explosives (see Figure 3.1 for a visual depiction). This meant that the explosive detonator location was also constant throughout, which kept the directional force of the shockwave stable throughout the different tests. The experiments were set-up following the experimental methodology developed during several proof-of-concept studies (DuBois *et al.* 2017; Appendix A). The explosive material was always placed directly on the centre front of the target tissue, in an effort to direct the blast wave directly onto the target. This was done with a goal of achieving maximum spatial distance of any resulting fragmentation and for ease of placement for the explosive operators.



**Figure 3.1.** A visual representation of how the primer (the blue arrow) is placed into the secondary explosive charge (black circle).

In this project, it was important to employ search and recovery techniques that allowed for a complete and rapid search of the area. This was a key consideration in the development of the methodology, as one must consider the potential limited number of individuals on site to assist in implementing the search. As outlined in Dirkmaat *et al.* (2001), Reinecket and Hochrech (2008), and Symes *et al.* (2012), and dealt with briefly in the literature review (see Section 2), the Waldron Springs Protocol is a method that was designed for faster evidence recovery and spatial plotting in mass disasters. The high reliability and general widespread usage of this protocol was the primary reasons for applying this search technique in this project (Dirkmaat *et al.* 2001; Reinecket and Hochrech 2008; Symes *et al.* 2012). This technique is divided into four parts:

- The first step is to search and locate the physical evidence, which in the case of these experimental tests was the tissue fragments;

- Second, employing a total station to collect the data and assign a field specimen number;
- The third step is the detailed photography of the evidence; and
- Lastly, the evidence is collected, preserved, and then removed from the scene.

In the course of this research only step one through three will be employed as there is no need to collect any of the tissue fragments (the subsequent analysis of the tissue fragments is outside the remit of this project). In experiments where multiple tests were being conducted on the same site, spray paint was used to distinguish the fragments in an effort to prevent any confusion between tests.

### **3.2 Scaling the target size**

One of the main goals of this PhD is to develop the foundational stages of an evidence database that practitioners can draw upon when they are investigating explosive events. In order to facilitate this, and to create a truly useful database, a large number of samples inherently must be examined; this is so general conclusions about this topic can be identified and explained (Edwards 2009; Edwards 2010; Morgan *et al.* 2009). In many facets of forensic experimental work this is not always possible, especially when there are number of limits and hurdles that prevent enough researchers from undertaking comparable work. One of these challenges is that obtaining large quantities of explosive material is very difficult due to restrictions on who can handle it. To address this issue, and to address research question 3.1, the option of conducting scaled experiments based on the full size pilot studies was explored (see DuBois *et al.* 2017 and Appendix A for more detail). In designing experiments that are scaled in nature, it reduces the cost and hazards that are often associated with this type of research.

Another major challenge is acquiring material to test upon, particularly when that material is biological tissue. These materials are inherently expensive to procure and then there is transportation of full-grown animals (to best approximate an average size human) to the experimental location, which can be difficult. Furthermore, there is another hurdle to overcome, and that is actually finding a suitable location to undertake these experiments. Many test ranges (for explosives or projectiles) do not permit biological



tissue to be exploded on their range. This is due to the risk of contamination and impact to the ranges ability to examine the chemistry associated with an explosive as discussed further in section 3.2.1.

In using a scaled biological tissue model instead, it potentially opens up the areas which can be used (as the area of potential contamination would be lower) and also could reduce the other challenges in material acquisition. The simplest solution to finding a ‘scaled’ biological tissue model was to employ piglets as they are just smaller versions of the large pigs used in the pilot experiments (see Appendix A). Piglets are also commonly used and documented within the medical field, and are also used as models in forensic decomposition studies (Catts and Goff 1992). They are also much cheaper to obtain from both veterinary schools and farmers, as they have either been stillborn or have died in an accident. This means that they no longer have any monetary value to those parties. It should be noted that the large pigs that were employed in the previous study were not adults but full grown juvenile. Farmers will wait till the pig gains its maximum weight, which occurs before reaching full adulthood (Belœil *et al.* 2014). This means that in all instances in which biological tissue was used involved juvenile pigs and was another reason why piglets were chosen. For these reasons, piglets were chosen and employed in the following experiments (with ethical approval throughout) as the scaled biological tissue substitute.

### **3.2.1 Using alternative target materials**

The experiments that were conducted throughout the course of this research not only focused on the scaling of biological tissue but also examined the use of non-biological tissue substitutes (research question 3.2). As mentioned above, in experimental forensic research obtaining the materials can often be just as challenging as conducting the actual experimentation due to the high costs or not having adequate facilities to undertake said experiments. This is especially true for ballistics-based experimentation and research, meaning that forensic scientists do not conduct experiments in this research area, which creates a gap in the knowledge base. The use of gelatine has been explored in separate areas of explosive research, mostly within the fields of improving protective materials and structures to prevent/limit personal injury (Carr 2016). However, the use of the gelatine as a substitute to biological tissue with the main objective being the creation of fragmentation is a new and unique approach.

The exploration of an alternative tissue target, specifically here being gelatine (refer to section 2.5.2), is an important step in opening up this area of experimentation to more scientists. To obtain a suitable gelatine model, a number of avenues for the making and the casting of gelatine were explored. Initially, an artist's drawing mannequin was used to create a practice model; this was selected as its height (12inches) closely resembles that of the piglet targets. Silicon T 20 was chosen as the modelling material. The joints of the mannequin were then glued in place to provide stability during the moulding process. Gaps between the joints were then filled in to allow for a more complete mould to form around the mannequin. Clay was then used to form a base for half of the mannequin to sit in. Once the sides of the clay by the mannequin had been levelled, wooden planks were placed on all four sides to hold in the silicon T 20 in place as it poured over the top of half of the mannequin. After waiting 24 hours for the silicon to set, the model was flipped over and the clay that forms the back of the mould was removed before more T 20 was poured. After waiting another 24 hours for the material to set, the model was divided in half along the pouring line and was determined to be complete.

This model, however, was not used in any of the experiments. One reason was that the model only allows for a single pour and would not accommodate the numbers needed for the larger scale experimentation that was planned. The second reason, due to ease of access to experiment space and materials, the experiments also took place in the United States, so it was impractical to transport the model to create the gel blocks on site. Another reason is that as the models would be filled with homemade gelatine, and there would be inherent difference between batches in both constancy and composition (Nicholas and Welsch 2004, 5). As one of the main purposes of this project is to develop a robust empirical database, it is vital that the baseline data is created using material that contains little to no variation between test subjects. Therefore, it was decided to order pre-made gel blocks from Clear Ballistic. This company employs FBI and NATO standards for replicating human tissue in ballistic testing (Clear Ballistic Gel: FAQs 2017); this was achieved by calibrating and employing batch controls to ensure that each gel block was similar to the others. Another issue with using homemade gelatine is that it is primarily made of gelatine based material. This means that if it is not stored in a refrigerated space and used within 72 hours of being poured it goes bad and cannot be used in any experimentation (Jussila 2004, 96). By purchasing the gelatine in a gelatine-free synthetic

material it meant that cool storage was not necessary and the blocks could be stored over long periods of time if any delayed occurred. The construction of the gelatine models was a useful exercise in how to create realistic models.

Once the type of gelatine block had been decided upon, it was necessary to undertake a small pilot test to observe if they could act as an appropriate substitute for the biological tissue. Several blocks of gelatine were purchased and exploded to obtain a general idea of how the gel would fragment. It made little sense to conduct large scale experiment comparing the two tissue targets if the gel did not fragment in a similar fashion to real tissue. The piglets chosen for the scaled tissue substitute were about 1/6th the total size of large pigs in weight and length dimensions (around 30.48L x 10.16W x 10.16H (centimetres)), a similar size gelatine target was chosen and ordered from Clear Ballistic. The gelatine blocks that were ordered measured 22.86L x 10.16W x 10.16H (centimetres) (the company in which the blocks were purchased employed US Imperial measurements; 9x4x4 inches) and slightly differed from the average piglet measurement (Figure 3.2 demonstrates the similarities between the two targets). This, however, was determined to be an acceptable difference due to the difficulties of making, storing, and transporting the materials to make the gel in-situ. These tests were undertaken in May 2015. Although there were several problems with the total station equipment not loading the spatial data correctly, the overall conclusion was that the gel fragmented enough to warrant investigation in large scaled testing.



**Figure 3.2.** A photograph which shows the relative size of the piglets compared to the gelatine blocks that were employed in the scaled experiment.

### **3.3 Scaling the explosive amount**

Working with explosives, especially in large quantities, is not only expensive but can also be dangerous. This further limits the number of experiments that can be conducted in this research area and the ability to expand the evidence base. This further indicates that less is understood about this important element within the field of forensic science. If it is possible to use scaled tests (if they produce a similar result to those conducted using a full-sized target) this could potentially facilitate more and higher quality research in this field of study. One advantage in using scaled materials is that multiple tests can be run within a single day, thereby increasing the number of results that can be obtained (Kleine *et al.* 2003, 124). There are several scaling methods that allow the results of smaller scale experiments to be applied to large scale tests and have been extensively confirmed on all scale sizes (Kleine *et al.* 2003, 128 - 129; Hargather and Settles 2007, 215). In terms of explosives, it is important for the scaling process to take into account the energy that is released and the strength of the blast wave. The scaling method employed here was based on the volume of the explosive which was selected as it is the simplest and most straightforward scaling method (Kleine *et al.* 2003, 128 - 129; Hargather and Settles 2007, 215). Since 3 kgs were used in the large pig pilot study (Appendix A), the scaled amount correlates to the size of the tissue targets; in the case of these experiments, the target tissue was approximately 1/6<sup>th</sup> of the size of the full grown biological tissue targets so 1/6<sup>th</sup> of the original 3 kgs of explosive meant that only 0.5 kgs were needed in the scaled tests.

### **3.4 Application of the Methods throughout each of the Experiments**

Within each of the three experiments that took place during the course of the PhD, the various methods that were discussed throughout this chapter were employed. Every effort was made to keep the method approach similar across all of the three experiments. In the following section, an overview of the application of the methods within each of the three experiments is discussed in more depth.

### 3.4.1 Methods Application within the Scaled Piglet Experiment

This experiment took place within a quarry site near Allentown, PA, USA (Figure 3.3) where the wind speed was recorded at 14 mph (in a south-easterly direction) at its highest; this was a limiting factor and will be explored further in the subsequent discussion chapter. The site area employed was very flat and covered with a fine dust. The site was flanked by rock piles which walled off the site on three sides. Five piglets were placed upright (achieved by surrounding each of the piglet with rocks, see Figure 3.4) each was separated by 30.48 meters (measurements were taken using an US Imperial measurement tape; 100 feet separated the piglets) in an attempt to prevent commingling between tests. Since the piglets were scaled tissue targets, the explosive amount that was used was also scaled. The amount of explosive was  $1/6^{\text{th}}$  of the amount of the explosive that was used in the pilot studies (3 kilos of C4 (DuBois *et al.* 2017 and see Appendix A), or 0.5 kgs of C4. The explosive was then placed on the centre of the piglet's chest with the primary charge placed directly into the block of C4. This allowed for the complete force of the explosive to be blasted directly into the piglet, resulting in maximum fragmentation distance. The centre piglet (recorded as piglet 3) was blasted first to determine if the distance that separated the piglets would be enough to limit commingling. Once the site was determined to be safe, the fragments were located using a line search, with two people identifying the fragments and the third following behind to mark the fragments with colour spray paint. Once this process was completed it was determined that in order to reduce the risk of commingling of fragments further, the ideal strategy was to blast the remaining piglets in pairs. The piglets labelled two and five were next blasted. This process was repeated for a final time with the piglets labelled one and four. The location of each piglet can be observed in Figure 3.5. The bomb was placed on the side of the piglet facing away from the quarry wall, as indicated by the placement of the piglet number. Each resulting spread was marked with different coloured spray paint in different shapes as to remove any confusion that may arise due to commingling.

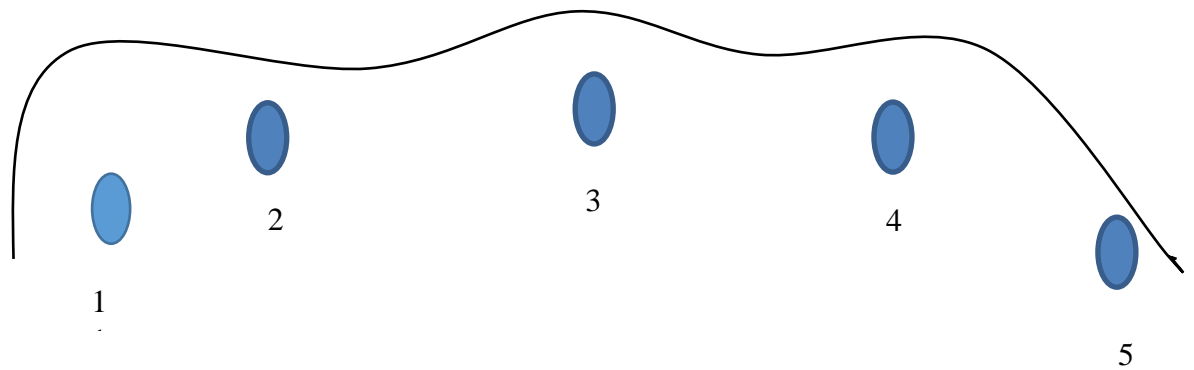




**Figure 3.3.** A photograph showing the quarry space that was used to conduct the test associated with this experiment.



**Figure 3.4.** A photograph demonstrating how the piglets were placed upright using rocks to surround the bodies



**Figure 3.5.** A map detailing the location of the five piglets that were used in this section of the experiment (not to scale).

A robotic Trimble S6 Series total station was used to collect the spatial data. The points were recorded in the total station and immediate afterwards a photograph with a scale was taken of the same fragment (see Figure 3.6). The scale was attached to a wooden stick in order for quicker insertion next to the fragment and to speed up the documentation process.



**Figure 3.6.** A photograph demonstrating the scale used when taking the photographic evidence of the fragments.



### 3.4.2 Methods Application within the Large Ballistic Experiment

Following the basic methodology that was discussed in section 3.1, the single gelatine torso was placed in the middle of the quarry site with the block of C4 weighting .68 kgs placed directly on the centre front of the block. This was done to direct the full force to the blast into the target to produce maximum fragmentation and maximum distance obtain by those fragments. The size of the gel blacks was 50.8 centimetres by 45.72 centimetres by 22.86 centimetres (order from a company that employed US Imperial measurements; 20 inches x 18 inches x 9 inches) and weighed 27.2 kilograms (60 lbs) (see Figure 3.7). The gel torso cost 360 British pounds to purchase and ship to the researcher.



**Figure 3.7.** The large gelatine block with the .68 kgs (amount was determined using an US Imperial scale; 1.5 lbs in pounds) of C4 explosive placed directly onto the middle of the target.

Once the single blast had occurred, a Trimble S3 series robotic total station was employed to mark the location of the fragmentation of the torso. The three bomb technicians from the Montgomery County Sheriff's Bomb Squad, and the FBI field office bomb technicians provided additional help by conducting a line search across the quarry site. When a fragment was located, the technicians would mark the location by circling



the fragment in spray paint. Once the fragment had been recorded using the total station, an 'x' was drawn through the circle to mark that it had been recorded (see figure 3.8).



**Figure 3.8** A photograph demonstrating how the fragments of the ballistic gel block were identified by the search team.

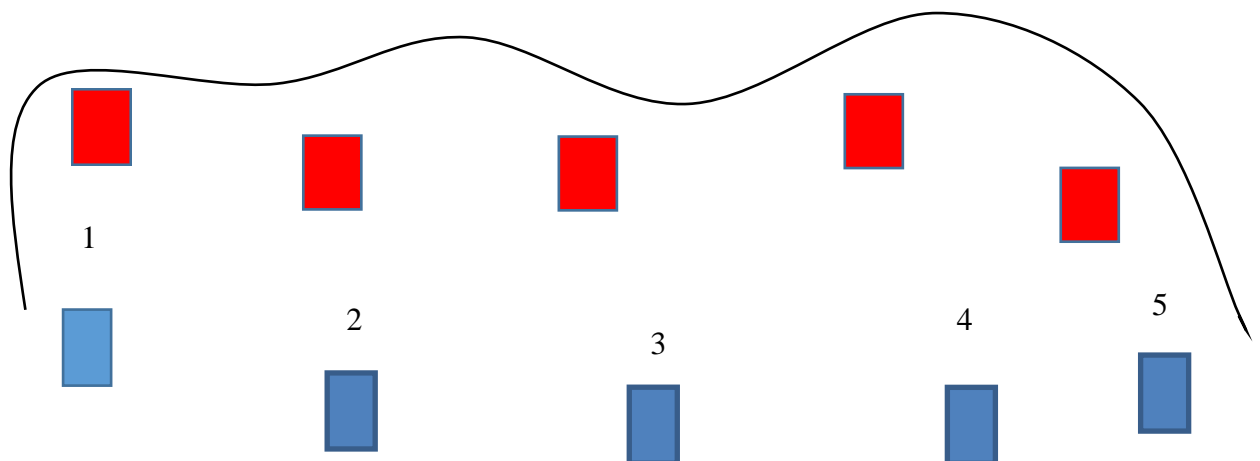
### **3.4.3 Methods Application within the Scaled Ballistic Experiment**

After the completion of the piglet tests, all of the scaled gelatine tests were conducted. The five gel blocks were placed 30.48 meters away from each other (measurements were taken using an US Imperial measurement tape; 100 feet separated the gelatine blocks) and 0.5 kgs of C4 explosive was placed directly on the front centre of the gel. This made the gelatine experiments directly comparable to the piglet, with the primary charge placed directly into the centre of the explosive charge to direct the majority of the force into the target. The first blast (gelatine block 3 in Figure 3.10) was once again blasted alone to observe if there was enough space between targets to prevent commingling of gelatine fragmentations. After the blast fragments from the first explosion were located and marked with colour spray paint, the second and fifth gel blocks were tested. Once complete, the last two gelatine blocks (one and four) were tested and the results marked. The location of all five gelatine blocks can be observed in Figure 3.10. It should be noted that the bomb was placed on the side of the gelatine block facing

towards the quarry wall, as indicated by the placement of the number. The differences in placement of the gelatine block from the piglet test targets was aimed at trying to preserve the blast centre of all of the targets within this confined space.



**Figure 3.9.** A photo comparison of the size of the both the piglets and the gel blocks that were used for this portion of the experiment.



**Figure 3.10.** A map detailing the location of the five gelatine blocks that were used in this section of the experiment (not to scale). The location of the piglets is also included and represented by the red squares.

After all the fragments from the gelatine test had been marked, as in the earlier experiments, a robotic Trimble S6 Series total station was used to collect the spatial data. The points were recorded in the total station and immediate afterwards a photograph with a scale was taken of the same fragment (see Figure 3.6). The scale was attached to a wooden stick in order for quicker insertion next to the fragment and to speed up the documentation process.

### **3.5 Conclusion**

The methods development described in this chapter were aimed to address the aspect of creating realistic forensic scenes to produce experimental data that can be used to develop a workable evidence data base. By exploring the use of different target materials and sizes, what can and cannot be employed within these experiments can be identified. With more options available to researchers to conduct experiments, it is hoped that more will undertake this type of research and build up a realistic evidence database that can be used by both researchers and practitioners in the field. The following chapter (Chapter Four) will focus on the statistically program that was developed to analysis the data that was collected during the experiments.

## **Chapter Four. Mapping and Statistical Methods**

To achieve one of the overarching goals of this project, a primary objective was to examine the spatial distribution patterns of tissue fragments created during an explosive event. To take the first steps towards achieving this goal, the precise location of each fragment from each explosive event was recorded using a total station and was collected and transferred from the total station onto the researcher's computer. Total stations are a commonly used tool within in the field of forensic archaeology and are often used with crime scene reconstruction (Dirkmaat 2012). The data points were then processed through Excel and imported in R Studio. In R Studio it was possible to plot the fragments as points around the blast centre. Next, several statistical tests were conducted in order to examine and describe how the tissue fragments fall around the blast centre.

### **4.1 Statistical Model**

In order to compare different conditional variables that may be present in investigating these types of events (in this case the size and the type of material), it was necessary to develop a method to map and compare the final spatial shape/position of the fragments. To achieve this, a number of forms of mapping and analysis were developed that could be applied to any fragment based data set resulting from an explosion. A unique program was developed in R by this PhD candidate, which implemented several different statistical tests.

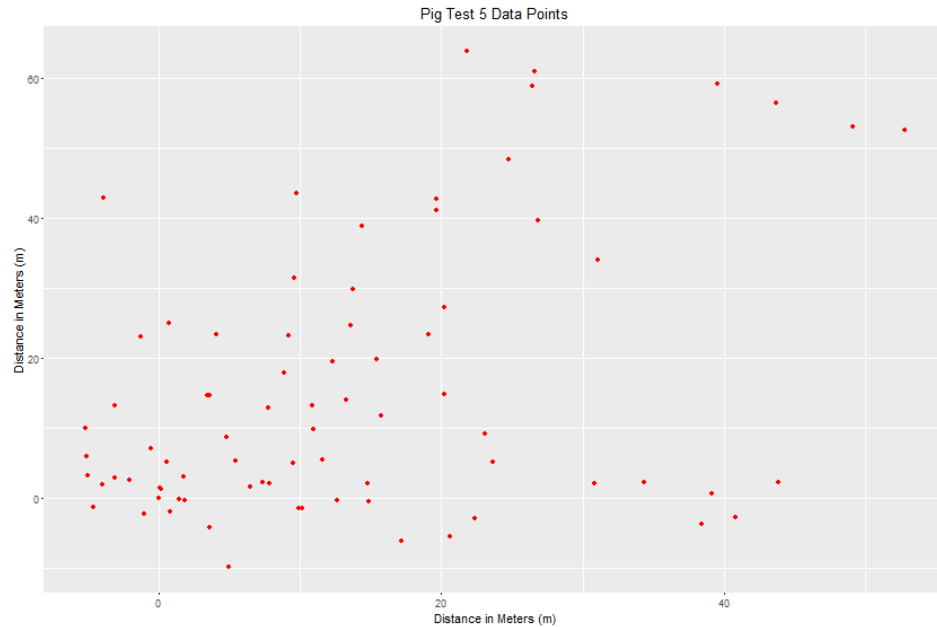
The resulting program undertook the following steps (each illustrated in more detail below the summary):

1. Plot of the point patterns of debris from each single explosion distribution (and the complete accumulating data across explosions) were created;
2. A linear regression line (a line of 'best fit') was employed that traced through the point of origin of the explosion and thus identified the direction of the blast;
3. A Kernel Density Estimation plot (KDE) was used to map the spatial pattern of the tissue and to identify general areas of high and low fragment concentration;

4. A cumulative density graph was created to identify the distance in which 25, 50 and 75 percent of the fragmentation was located;
5. A distribution bar graph was produce which summarised the spatial spread of material across 5 metre distance bands. This was used to identify similarities and differences across data sets using a visual representation of the fragmentation distribution;
6. The blast was statistically characterized to determine both the uniformity and direction of the fragment distribution. This was achieved with the use of circular statistics, Rayleigh's Test of Uniformity and Watson-Wheeler test;
7. The R program also had elements which enabled the comparison of different explosion data sets to each other both descriptively and statistically. This was achieved through:
  - examining the total distance/data spread travelled by the fragmentations using cumulative density graphs;
  - comparing the average distance of fragmentation percentages (Q1, Median, and Q3) and the fragment density in 5 meter distance bands using bar density graphs;
  - rotating the KDE plots to enable shape comparison;
  - using a statistical cumulative density comparison which employed a Kolmogorov–Smirnov (KS) test.

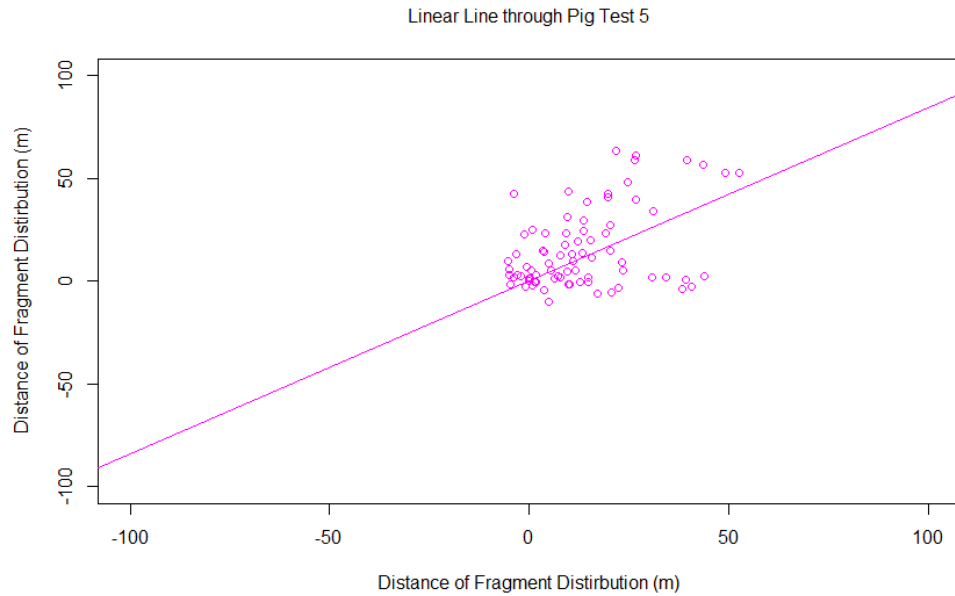
The above gives an overview of the methods employed, but it is important before moving on to the experimental results that each of these steps are described and illustrated in detail. Figure 4.1 gives an example of method step 1. It is a visual representation of the data point plot. This demonstrates the overall spatial spread of the fragments with the blast centre position at (0,0).





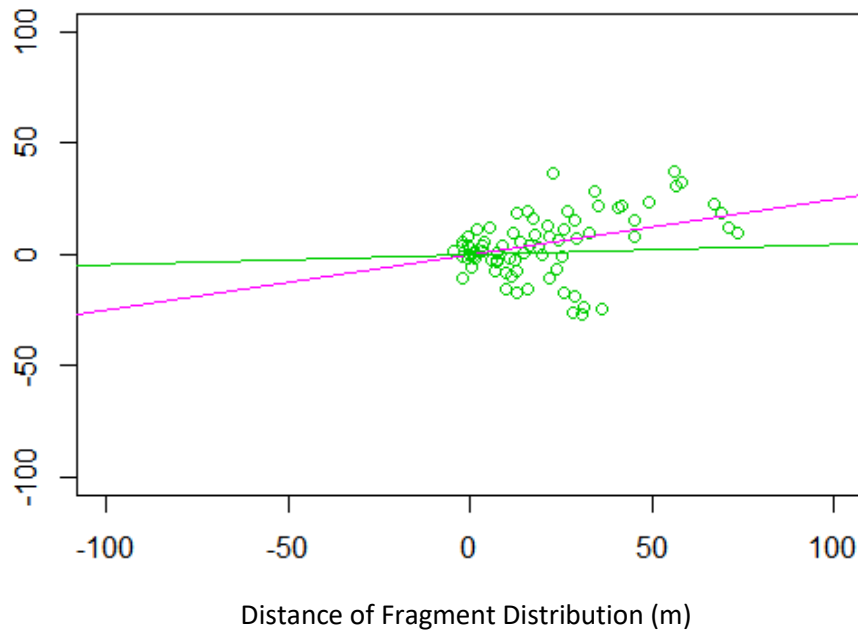
**Figure 4.1.** A visual representation of the data point plot. This demonstrates the overall spatial spread before the placement of the linear regression line through the data set. The blast centre has been position at (0,0).

In the second step of the analysis process, a linear regression line (calculated using a linear regression formula) is plotted through the spatial data spread (see Figure 4.2 for a visual demonstration). It is, in essence, a line of best fit which is calculated by regressing the x co-ordinate against the y co-ordinate. This also acts to visually represent the general direction of the spatial spread. This can also be employed to tie the spatial data to a line that can be rotated around the centre point so that it can be compared to other data with all the blast directions lined up and thus controlled for. In this case, the procedure ensures the angle and distance between the points remains constant.



**Figure 4.2.** In the second step of the analysis process, a linear regression line (calculated using a linear regression formula) was plotted through the spatial data spread.

This use of a linear regression line (between the horizontal and vertical co-ordinates of the blast) to represent the blast direction is completely novel. This statistical method is usually used to look at the correlation between two variables (Field 2009, 198; Agresti and Finlay 2009, 255). By defining the blast direction as a linear regression line through the centre of the data set it makes it possible to line up multiple tests and for comparisons across models to occur. Figure 4.3 shows a plot which has data on it from two different explosions. The lime green data points and line corresponded to pig test 5 and the red line correspond to pig test 1. It is interesting to compare the direction and pattern of these two distributions.

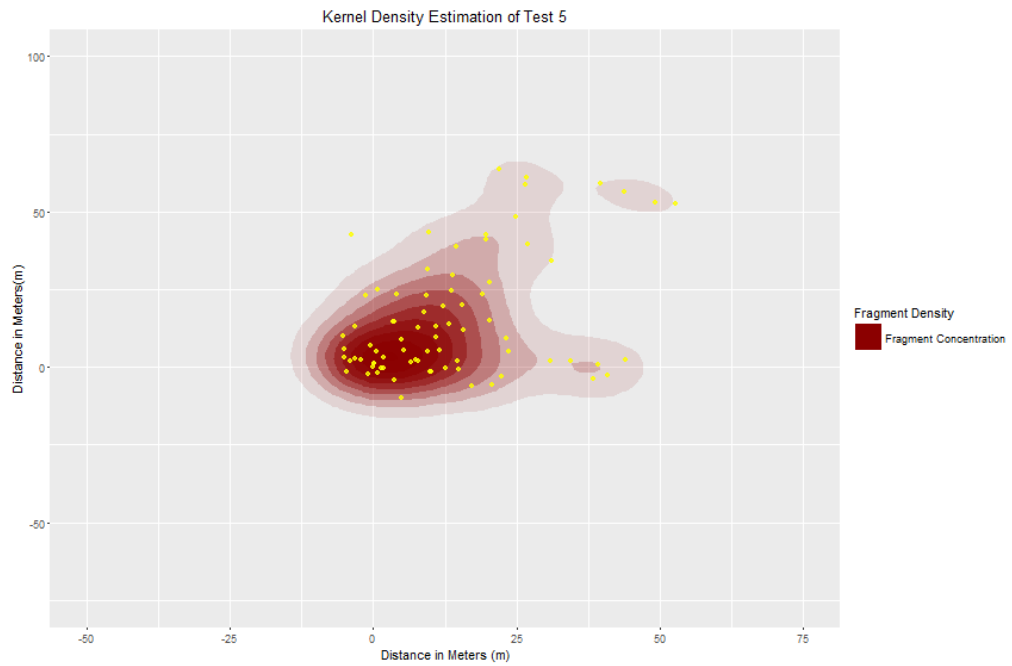


**Figure 4.3.** The distributions of two experiments compared on one plot.

Anchoring each experiment with a blast centre and a line of best fit also allows data sets to be rotated around their central points until the blast direction of all are aligned (see Figure 4.3 for a visual depiction). This allows for comparison of spatial spread between experiments while keeping the distance between the angles of the fragments the same. A useful way to explain this concept is by comparing it to fingerprint analysis. Fingerprints are often found in different positions and angles; by rotating the different fingerprints so that they are positioned in the same direction and lining them up on top of each other, an individual could compare fingerprints and reveal any differences that may exist between samples. By generalizing the test patterns, distinct variations can be studied and explored.

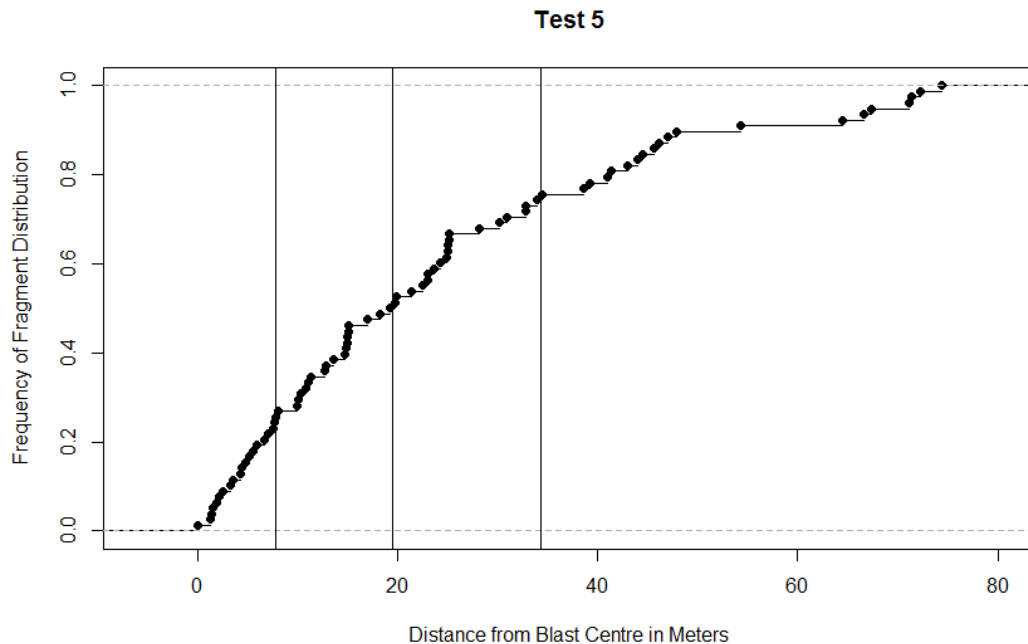
The next step in the R studio program was to use a KDE test to visually identify the areas around the blast centre where the greatest amounts of fragments tend to be located. These cluster areas are identified as ‘hot spots’ and are represented in different colours on a scaled process going from bright red (representing areas of the highest count of fragments) to pale red (representing areas of with few to no fragments) (see Figure 4.4 for a visual depiction).





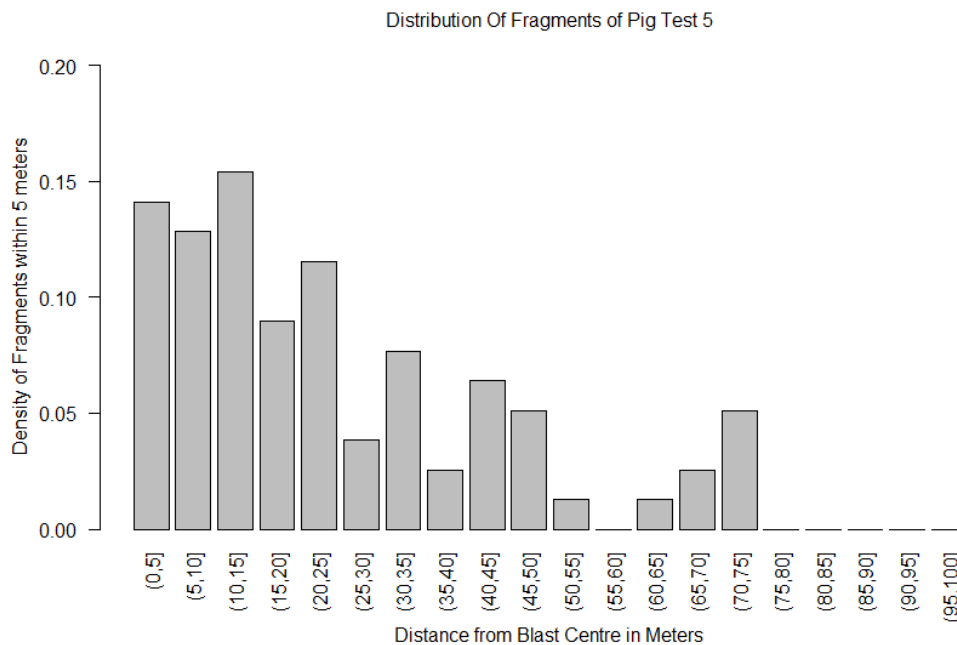
**Figure 4.4.** An example of a KDE test, which demonstrates the density of the fragments around the centre of the blast site. A yellow dot represents a single tissue fragment.

Next, a cumulative density graph was created; this is a different way of describing the density clustering as identified in the KDE plots. This test breaks down the concentration of the fragment distribution by examining the physical distances in meters at which 25%, 50% and 75% of the fragments were located scanning outwards from the centre of the blast (Figure 4.5).



**Figure 4.5.** The data was then processed to produce a cumulative density graph with vertical lines to identify the distance at which 25, 50 and 75 percent of the total fragmentation was recorded.

This fragment density distribution was explored further by creation of a ‘density of distribution’ bar graph which illustrated the percentage of fragments found in every 5 meters distance band from the blast centre (Figure 4.6).

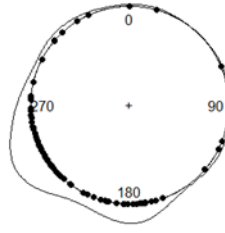


**Figure 4.6.** An example of a distribution bar graph which visually represents the fragment distribution location every 5 meters.

Once again this test was used to expand on the location of the fragmentation and is an important step in identifying where the majority of the fragments would most likely

be located. The ability to identify the likely location of the fragments is an important aspect of helping to develop more accurate search and recovery techniques, for example, a more effective search grid. With a more accurate estimate of a search grid which is likely to fruitfully discover fragments, more evidence can be protected in-situ, a vital aspect of any forensic investigation. This idea of establishing a quick search grid can also be applied in cases, like those in conflict zones, where a scene needs to be processed in an expedited manner. Post-blast scene are not only chaotic, they are also inherently dangerous. From the risk of secondary attacks occurring against first responders and investigators, to the environmental hazards that may have been released (i.e. hazards dust particular, chemical components, etc.), the need to quickly process a scene is one of the main means of migrating these risk factors (FEMA 2002; U.S. Department of Homeland Security 2013; Thomas et al., 2014). By knowing the likely range of the spatial distribution, practitioners can arrive on a scene and immediately began to process it with little to no lag time.

To this point, the analysis described has been descriptive in nature and has concentrated on visually comparing fragment distributions. Circular statistics were also employed as a way to identify the direction of the blast spread. This section of the R studio program helps to identify the influence the precise placement of the bomb has on the target and the resulting directionality and shape of distribution of the fragments. In order to achieve this, the angle of the fragmentation was calculated in relation the blast centre, thus plotting the fragmentation as it would appear on a 360 degree circle. To begin by visually representing this, a circular graph was produced that illustrates the degree area with the highest fragment concentration (Figure 4.7) by indicating the general direction of the fragmentation spread from the centre of the blast. The unit degrees were calculated by first achieved by identifying the linear distance between the fragmentation point X and Y coordinates to the X and Y distance coordinates of the blast centre. That distance is then used to determine the direction of the angle using an inverse tangent, with the final angle calculated to remove any negative angle numbers.



**Figure 4.7.** A circular graph that demonstrates the degree area with the highest fragment concentration. In the case of the above graph, the majority of the fragmentation fell away from the blast centre.

In terms of circular statistics, Rayleigh's Test of Uniformity is used to examine the uniformity of a data spread and an example of this test is given in Table 4.1. This statistical test is shown in Figure 4.8.

$$S^* = \left(1 - \frac{1}{2n}\right) 2n\bar{R}^2 + \frac{n\bar{R}^4}{2}$$

**Figure 4.8.** Rayleigh's Test of Uniformity statistical formula (NCSS Statistical Software, 2017);  $S = \frac{\sum_{i=1}^n \sin \theta_i}{n}$ , n= data points, R= test statistic.

This statistical output demonstrates how uniform a particular data set is if compared to an equal spaced spread across a 360 degree circle. In essence, it explores the 'evenness' of the fragmentation spread and is therefore a statistical representation of any resulting fragment directionality (Jammalamadaka and SenGupta, 2001; Mardia and Jupp, 2009; Fisher 1995). For the purpose of this section of the R program, this statistical test was employed to indicate how much of an impact the placement of the bomb on the target had on the overall directionality and the location of the resulting blast fragments. Rayleigh's Test of Uniformity was not only chosen for its ease of use, but also since it is applied in a range of field sciences (i.e. ecology, biology, etc.) when examining data that is circular in nature (Nievergelt et al 1999). In the cases illustrated in Table 4.1, results from the statistical test show that there is non-uniformity across the experiments with the test statistics producing a p value that is significant in nature (less than  $p < 0.01$ ). These results demonstrate that the null hypothesis of a distribution that is equally spread across a 360 degree circle is not true when applied to this data set.

Test Number	Rayleigh Test of Uniformity Test Statistic	P -Value
Test 1	0.8593	p<0.01
Test 2	0.598	p<0.01
Test 3	0.366	p<0.01
Test 4	0.3178	p<0.01
Test 5	0.6658	p<0.01
Test 6	0.4554	p<0.01
Test 7	0.6562	p<0.01
Test 8	0.6242	p<0.01
Test 9	0.2952	p<0.01

**Table 4.1.** An example of the data output of a Rayleigh's Test of Uniformity.

A further statistic used in the data analysis in the experiments was the Watson-Wheeler test. The statistical test is displayed in Figure 4.9, with  $W_g$  representing the test statistic.

$$W_g = 2 \sum_{i=1}^g \frac{(C_{Ri}^2 + S_{Ri}^2)}{n_i}$$

where  $C_{Ri} = \sum_{j=1}^{n_i} \cos(\gamma_{ij})$ ,  $S_{Ri} = \sum_{j=1}^{n_i} \sin(\gamma_{ij})$ ,  $n = \sum_{i=1}^g n_i$ , and  $\gamma_{ij}$  are the circular ranks of the corresponding angles. The circular ranks are calculated using

$$\gamma_{ij} = \frac{2\pi r_{ij}}{n}$$

**Figure 4.9.** The Watson-Wheeler Test statistical test (NCSS Statistical Software, 2017).

This statistical test is used to compare the similarities of two or more circular data sets by examining and identifying if there are any significant differences between the uniformity of their spread over 360 degree. Given that one of the research aims posed by this PhD was to explore the use of different target materials and target sizes, the ability to compare and contrast the directionality of the different target materials was an important aspect of the overall data analysis. Like the Rayleigh Test of Uniformity, the Watson-Wheeler test was chosen for its commonality and its ease of use (Nievergelt et al 1999).

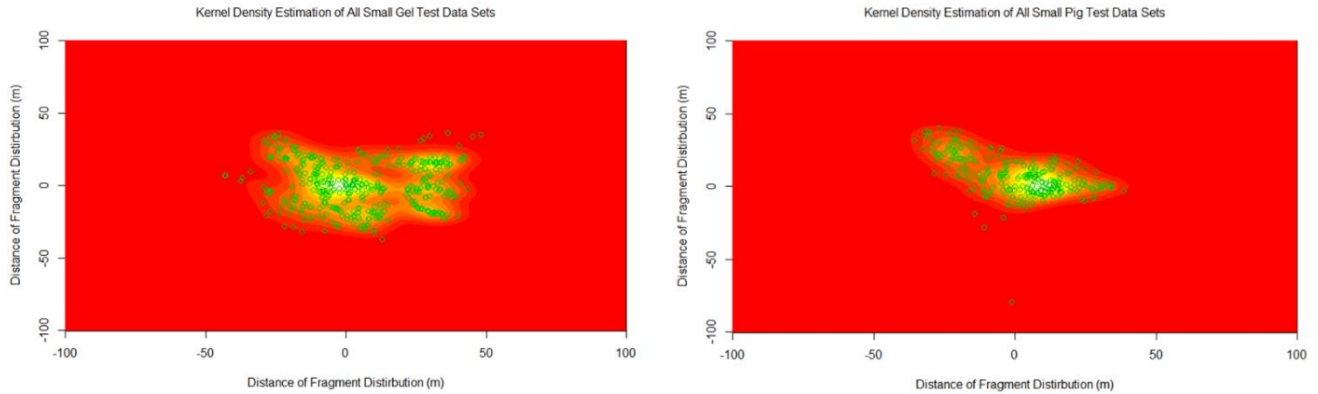
It was also chosen as a tool for the analysis process in that the test does not look at the general direction of the data but the overall shape of the distribution of each of the data sets and employs that in the comparison (NCSS Statistical Software, 2017). An example of Watson-Wheeler statistics from a sample of test comparisons are given in Table 4.2. Here, a p-value that is significant in nature ( $p\text{-value} < 0.001$ ) indicates that the compared circular data sets are not similar to each other.

Test Number	Rayleigh's Test of Uniformity Result	P-Value
Pig Test 1	0.7818	$p < 0.01$
Pig Test 2	0.398	$p < 0.01$
Pig Test 3	0.8833	$p < 0.01$
Pig Test 4	0.832	$p < 0.01$
Pig Test 5	0.8539	$p < 0.01$

**Table 4.2.** An example of a Watson-Wheeler test.

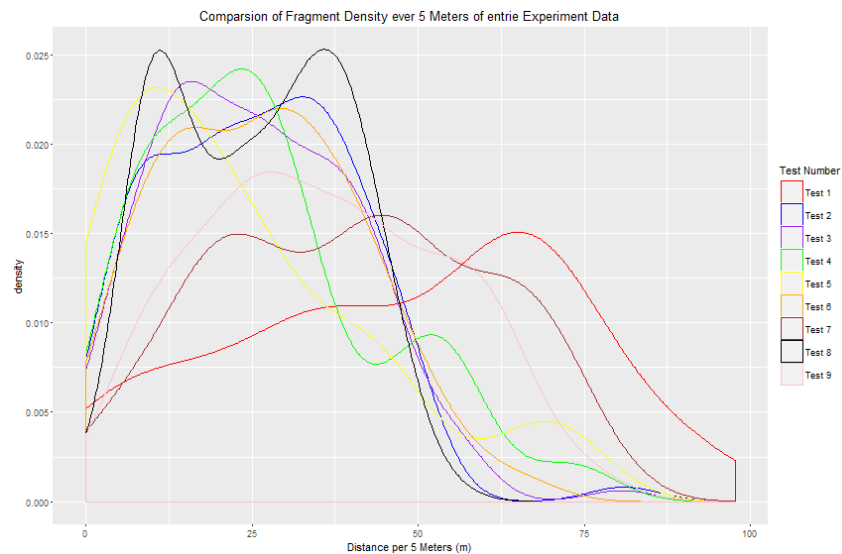
The R program was also used to compare the individual data sets collected from a single experiment (intra- group comparison) and the full experimental data to each other (whole group comparison) in more depth than the summary Watson-Wheeler tests. The comparison between the different experiments was important to address the PhD aims of exploring the use of different target materials and target sizes in conducting this type of forensic explosive research. In exploring the similarities and difference between the data sets, a more in-depth understanding of the possibilities of employing the different target materials and sizes can be obtained. To achieve this, further statistical tests were conducted. They included plotting the total distance/data spread travelled by the fragmentations using a cumulative density graph (see Figure 4.5), the average distance of fragmentation percentages (Q1, Median, and Q3) employing bar density graphs (Figure 4.6), comparing the overall rotated data sets within KDE plots (see Figure 4.10) and the percentage of the fragments per 5 meters moving out from the centre for a number of experimental tests on one graph (see Figure 4.11). The use of cumulative density graphs and bar density graphs have been discussed, but the use of the rotated KDE plots was

different from the previous use of KDE plots. Using the rotated data sets that were tied to the best-fit lines (see Figure 4.5 for a visual demonstration), the collective rotated data of each experiment was plotted. These rotated KDE plots (Figure 4.10) were then visually compared to each other as a method to observe similarities and differences between the overall spatial distributions of each experiment.



**Figure 4.10.** A visual demonstration of the rotated KDE plots that were employed as a visual means of comparing two data sets spatial distribution to each other.

The comparison of the fragment density per 5 meters (Figure 4.11) was another tool to aid in identifying commonalities and dissimilarities across tests by examining how similar the fragmentation spread was between different tests.



**Figure 4.11.** An example of the comparison of the fragment density across data sets.

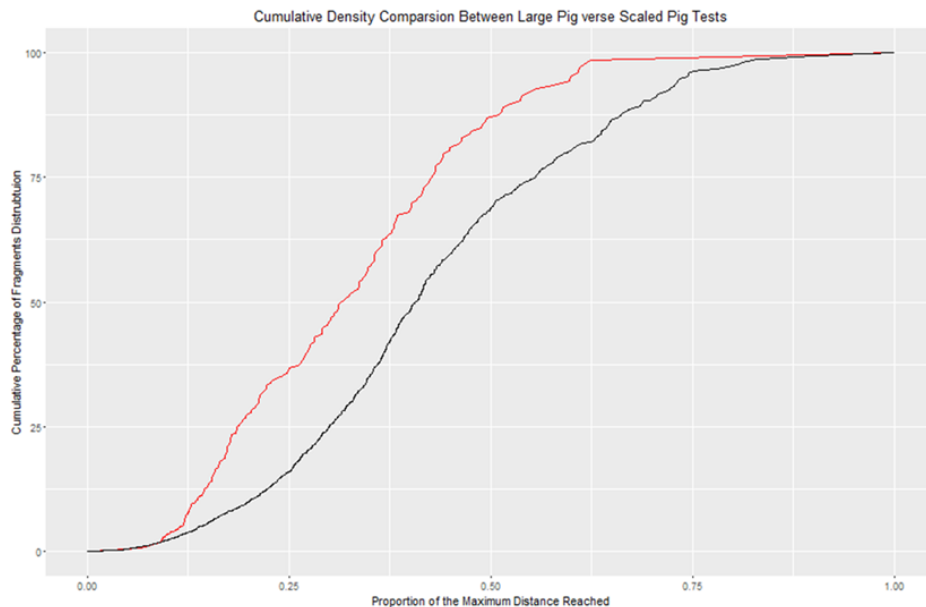
Lastly, a statistical cumulative density comparison was employed to compare the shape of the fragment distribution across the different experiments (see Figure 4.12). This was done by employing a Kolmogorov–Smirnov test or KS test to observe how similar or dissimilar the shape of the cumulative fragment distribution of the two data sets from any other two experiments are (NIST/SEMATECH, 2013). The KS test formula is displayed below.

$$D_n = \max |F_n(t_{(i)}) - F_0(t_{(i)})|$$

**Figure 4.12.** The Kolmogorov–Smirnov test formula (NIST/SEMATECH, 2013); with  $D$  = test statistic,  $F_n$  = sample distribution function,  $F_0$  = theoretical distribution function.

This comparison was only possible by controlling for the maximum distance of each fragment distribution. This was done by looking at the distribution of fragments for different proportions of the maximum distance achieved within a test. For example, in test A, 75% of the fragments might have been captured at a distance which was 50% of the maximum for any fragment found in that particular test. This figure might be 60% of the fragments for test B. By examining the distributions like this, any difference in the physical scale of the experiments has been controlled. This enables a fair comparison of the shape of the density distributions. An example of the results of a KS test can be observed from the comparison of the scaled piglets and the large pigs. This KS test produced this result,  $D = .34$ ,  $p < 2.2e-16$ , with  $D$  representing the distance between the two data sets and the  $p$ -value indicating how significant the difference between the two data sets are given that the null hypothesis for the KS test is that the two data sets are from the same data set. In the case of this example, the distance between the two data sets is significantly different and that they did not come from the same data sets. (NIST/SEMATECH, 2013).





**Figure 4.13.** An example of the cumulative density comparison graph produced from the KS test data. This was used to compare and contrast the shape of the fragment distribution across the proportion of the maximum distance.

## 4.2 Conclusion

The R studio program that was developed in the course of this PhD provided the ability to examine the similarities and differences between the different target materials was an important element the was developed in the course of this PhD. This program was important in interpreting the resulting data from the different experiments and identify what target materials and sizes work as usable comparable materials. This program also provides an insight into developing an understanding of how the different explosive variables impact the resulting fragmentation distribution. Although other area of explosive research, for example research into the development of body armour to protect individuals from explosive injuries (Cannon 2001), the area of tissue fragmentation is an avenue of study that had yet to be studied. With the development of this R program, it provides the scientific community with a new means of examining data produced during this type of explosive research. Future development of the program can be expanded into an aid for law enforcement to develop a workable database in which to help identify groups or individuals that may have conducted the explosive. As noted in section 2.2.2, explosive event will vary between groups and individuals based on materials and training available to them (Quillen 2002; Morely and Leslie 2006; Asal and Rethemeyer 2008). As noted different explosives types will produce differing tissue fragmentation distribution. It is in conducting more experimentation that identify those differences can

be employed to help to identify what type of explosive that was used and this information can then be applied in helping to identify those responsible for the explosive event. This use of the R program as a tool for law enforcement also be employed by practitioners to aid in developing an understanding of what occurred on the explosive scene prior to the blast happening.

In opening up this area to more testing, the intention is that it will aid in expanding the evidence base, an important part of increasing the validity of evidence interpretation and assess the reliability of forensic evidence (Morgan *et al.* 2009; Cook *et al.* 1998; Morgan and Bull 2007; Edwards 2009; Edwards 2010; NAS 2009; Mnookin *et al.* 2011). Each step of the program created in R Studio is designed to not only identify how far the fragments on average will travel but also to identify distance areas where the majority of the fragments will most likely land. It is also important to compare the shapes of the density distributions across explosions against each other. In developing an understanding of how this one aspect of the forensic scene is created (the overall spatial distribution of the fragmentation), more complex experiments can be created to build on the foundation of the workable evidence database. (Mnookin 2011; Morgan and Bull 2007; Cook *et al.* 1998; Ludwig and Fraser 2014; Morgan *et al.* 2009).

#### **4.3 Author's note**

The following three chapters discuss the four different experiments that were conducted as part of this PhD and then compares them to each other. The first of these chapters (Chapter Five) examines the large pig experiments and compares the results to the small pig experiments. This is the first set of comparisons conducted to address the first and fourth research question (see 2.6.1 and 2.6.4 respectively for more details) on how accurate a scaled model fragmentation is to the larger tissue target, since these experiments were conducted using the same tissue make-up. The second set of comparisons (Chapter Six) looks at the large pig results and the large gelatine results to address the second and fourth research question (see 2.6.2 and 2.6.4 respectively for more details) looking at whether or not a non-biological target would produce similar results to the biological targets. Lastly, the third comparison (Chapter Seven) examines a combination of both the first and second research question (see 2.6.1, 2.6.2, and 2.6.4 respectively for more details) in discussing the results from the scaled pig experiment to

the scaled gelatine experiments. The research question 2.6.3 and 2.6.5 are addressed in the chapter (Chapter Eight) that follow which examine the results of a large post-blast training exercise that was conducted, examining how realistic the outcomes of the experiments conducted in this PhD are to the results of a more real world situation. Research question 2.6.5 is further explored in throughout section 9.1.3 in the Chapter Nine/Discussion.

The chapters that examine and compare the four experimental results are structured in a manner that resembles an academic paper. Each of the chapters describes the experimental set-up and then the process for data collection. The results from the data sets for each comparison (e.g. small versus large pigs) are then described, followed by a discussion on the similarities and differences between the two data sets. This chapter structure was chosen because it clearly outlines how each of the four experiments was conducted, what the results from those experiments were and how the two data sets compare to each other. The chapters which examine the post –blast training exercise are split into two separate chapters. One examines the results from the search and recovery and the other discusses a series of questions put to the various practitioners who were present at the training exercise about how forensic evidence fits into their work. The results from of all four of the experiments, the post-blast training exercise and the answers from the series of questions are discussed in further detail in a discussion chapter which aims to address the themes put forth in the literature chapter and summarise the findings from each of the research questions.

## **Chapter Five. Large Pig Test versus Scaled Piglet Test**

With one of the goals of this current project to develop an experimental methodology that can be more easily applied by other researchers examining explosive events, the first issue that needed to be overcome was the issue of scaling. In this section of the thesis, the data collected from scaled experiments were compared and contrasted to the full-size experiments to observe if using scaled tissue targets is a reliable experimental method that can be applied in future experiments. The experiments described below were possible due to a close working relationship with the Montgomery County Sheriff's Office Explosive Ordinance Disposal (EOD) team located in Allentown, Pennsylvania, USA. This relationship began when the researcher was put in contact with the lieutenant in charge of the EOD team by an academic contact in the USA. This relationship developed over the course of four years, in which multiple experiments for this PhD were conducted along with participants in several law enforcement run training exercises. This relationship provided the researcher with access to explosive ranges that would allow the use of biological targets and access to C4 explosives. The piglets that were employed in the course of this set of experiments were provided by the academic contact free of charge. All of the equipment (targets and total station), along with the researcher were driven to the quarry site on the day of the experiments.

### **5.1 Large pig experiment overview**

The full-size pig experiments that were conducted as part of the MRes were aimed to establish the basic methodology that would be employed in the course of the PhD. Each pig was placed upright on a wooden stake with 3 kgs of military grade explosive placed in a bundle directly on the centre of the pigs' chests. The primary charge was placed directly into the centre of the explosive. This was done so that the blast force would be directed into the pig to try and obtain the maximum distance possible for the tissue fragmentation. Each pig was exploded and then the fragments from each test were located and marked with flags before being recorded with a total station. The area where the experiment was conducted was large enough that commingling of the fragments from

different tests was not an issue. The full results of these tests can be seen in Appendix A and in DuBois *et al.* (2017). Although a few basic statistics were performed on the spatial data, the goal of this experiment was to provide a stronger experimental methodology and to identify areas for future studies. The range and explosive company (located in the U.K.) were not further used due to the cost associated with using the company and the many noise complaints made by the residents to the local police authorities.

## 5.2 Scaled piglet experiments

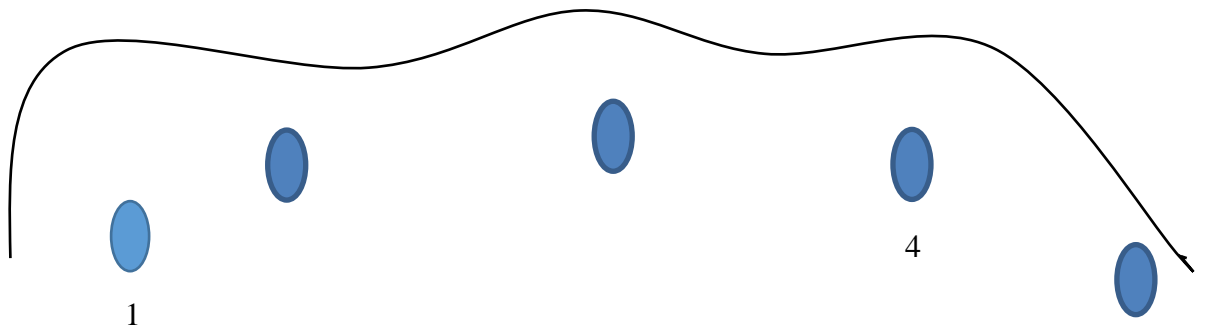
As discussed pervious in section 3.4.1, these experiment took place within a quarry site near Allentown, PA, USA (Figure 5.1). Five piglets were placed upright (achieved by surrounding each of the piglet with rocks, see Figure 5.2) each was separated by 30.48 meters (measurements were taken using an US Imperial measurement tape; 100 feet separated the piglets) in an attempt to prevent commingling between tests.



**Figure 5.1.** A photograph showing the quarry space that was used to conduct the test associated with this experiment.



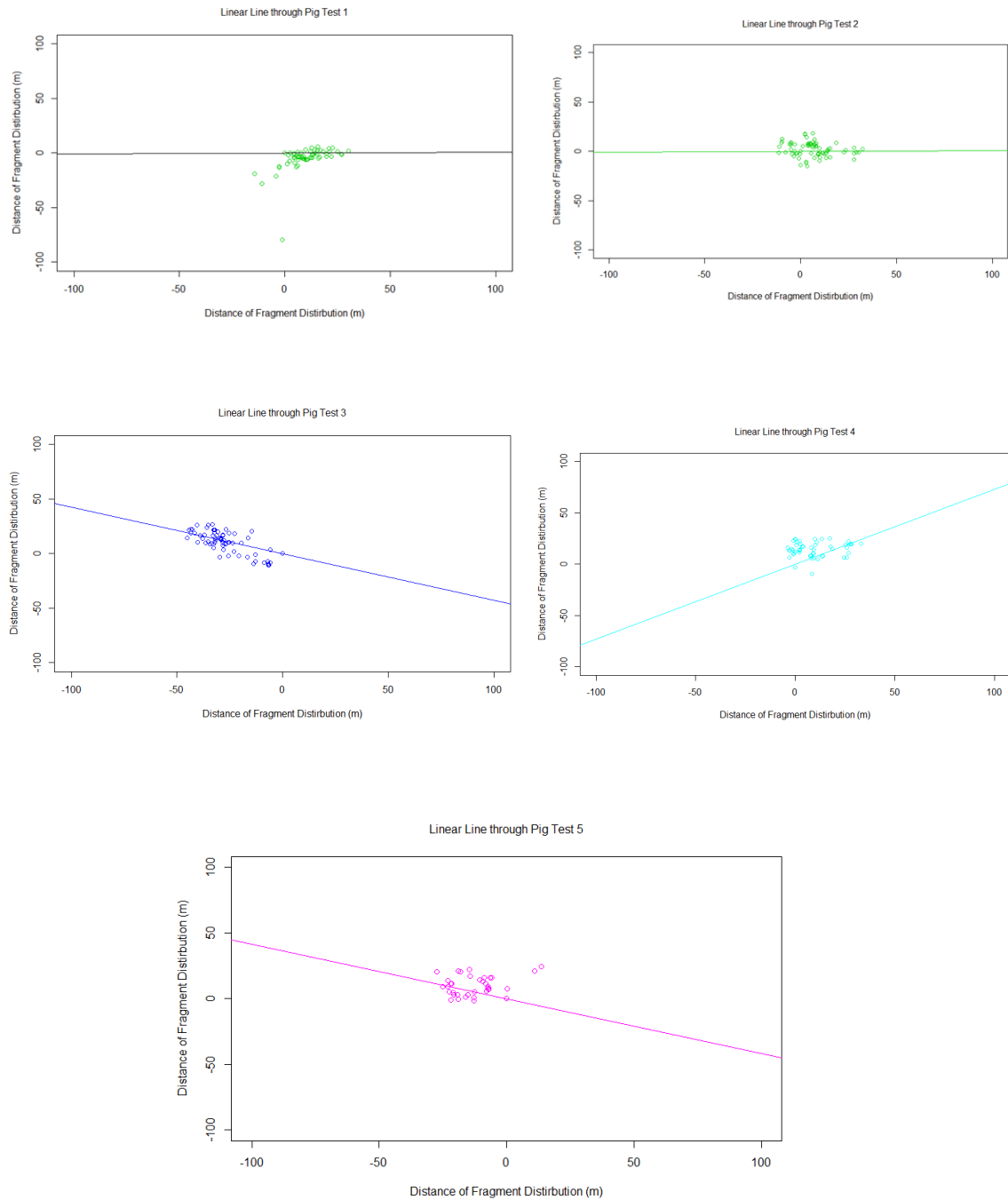
**Figure 5.2.** A photograph demonstrating how the piglets were placed upright using rocks to surround the bodies



**Figure 5.3.** A map detailing the location of the five piglets that were used in this section of the experiment (not to scale).

### 5.3 Piglet mapping results

The data was processed through the program in the same manner as the data from the previous pilot study (DuBois *et al.* 2017 and Appendix A). First a best-fit line was produced to tie the fragment points to their unique spatial location (see Figure 5.4) and as observed below the direction of the fragmentation spread differed between each of the piglets, due to the position of the explosive charge and primer on the target.

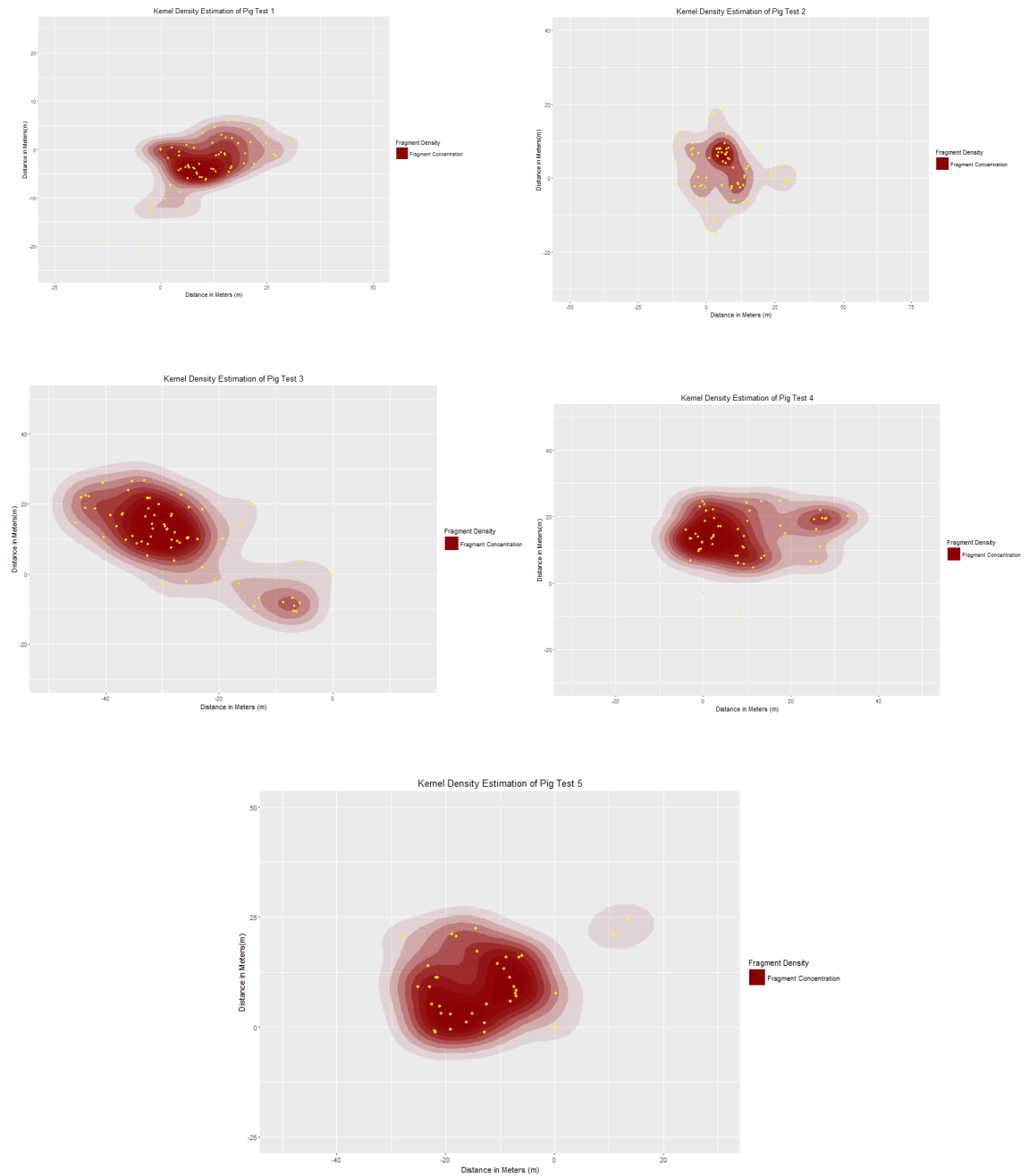


**Figure 5.4.** The best-fit line plots of piglet target data. The best-fit line was employed as a means of tying the fragment points to their respective spatial location.

The data was then processed using a KDE (see Figure 5.5), which demonstrated that the majority of the fragments landed near/at the blast centre and can be identified by



the yellow colour on the red background. This high density of fragmentation decrease as the distance from the centre of the blast increases.

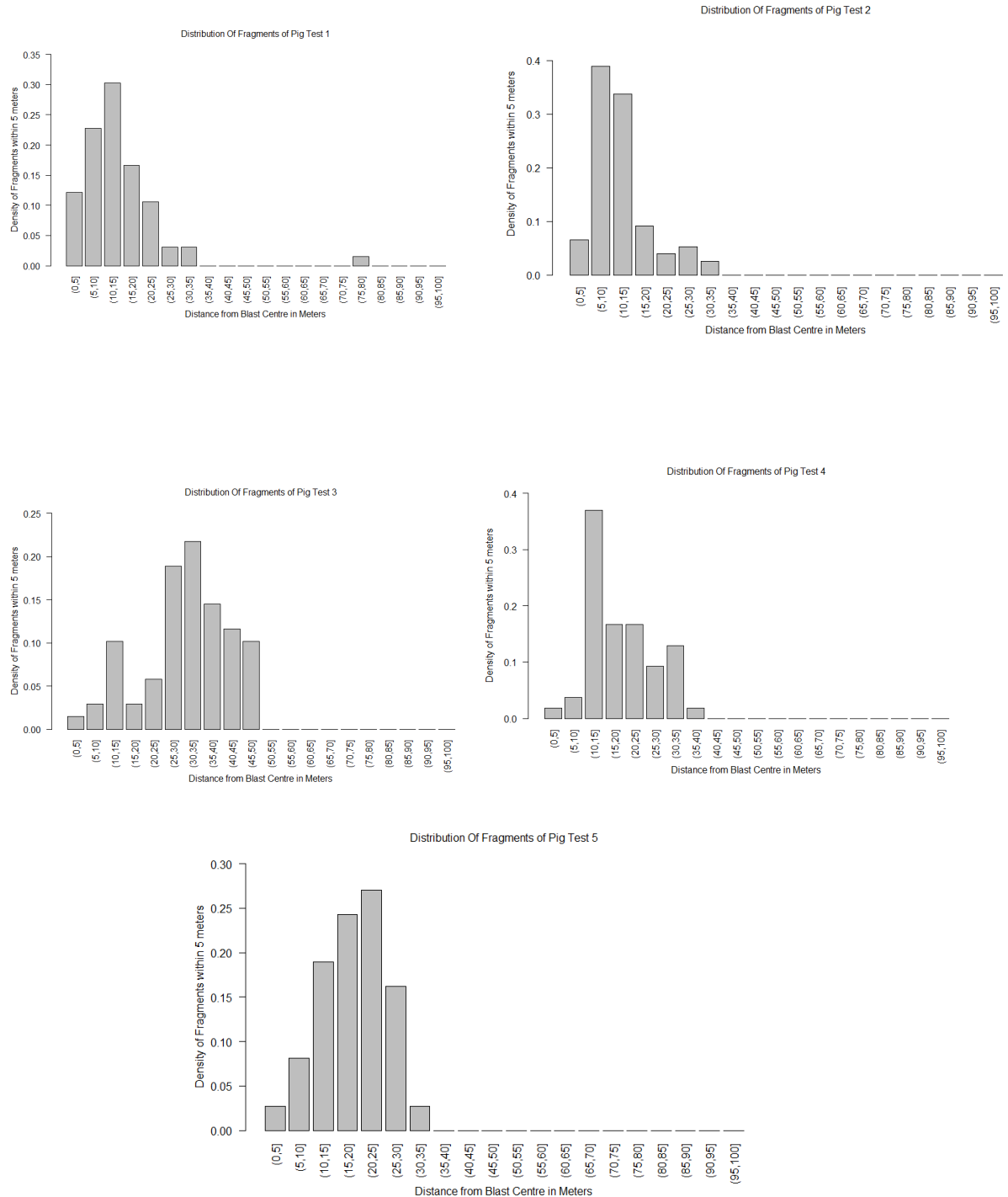


**Figure 5.5.** The KDE plots of the piglet targets

Next density bar graphs (see Figure 5.6) were employed to observe the percentage of the fragments ever five meters moving out from the blast centre. As it can be observed from the graph below, the fragments cluster in all of the piglet tests around the centre of



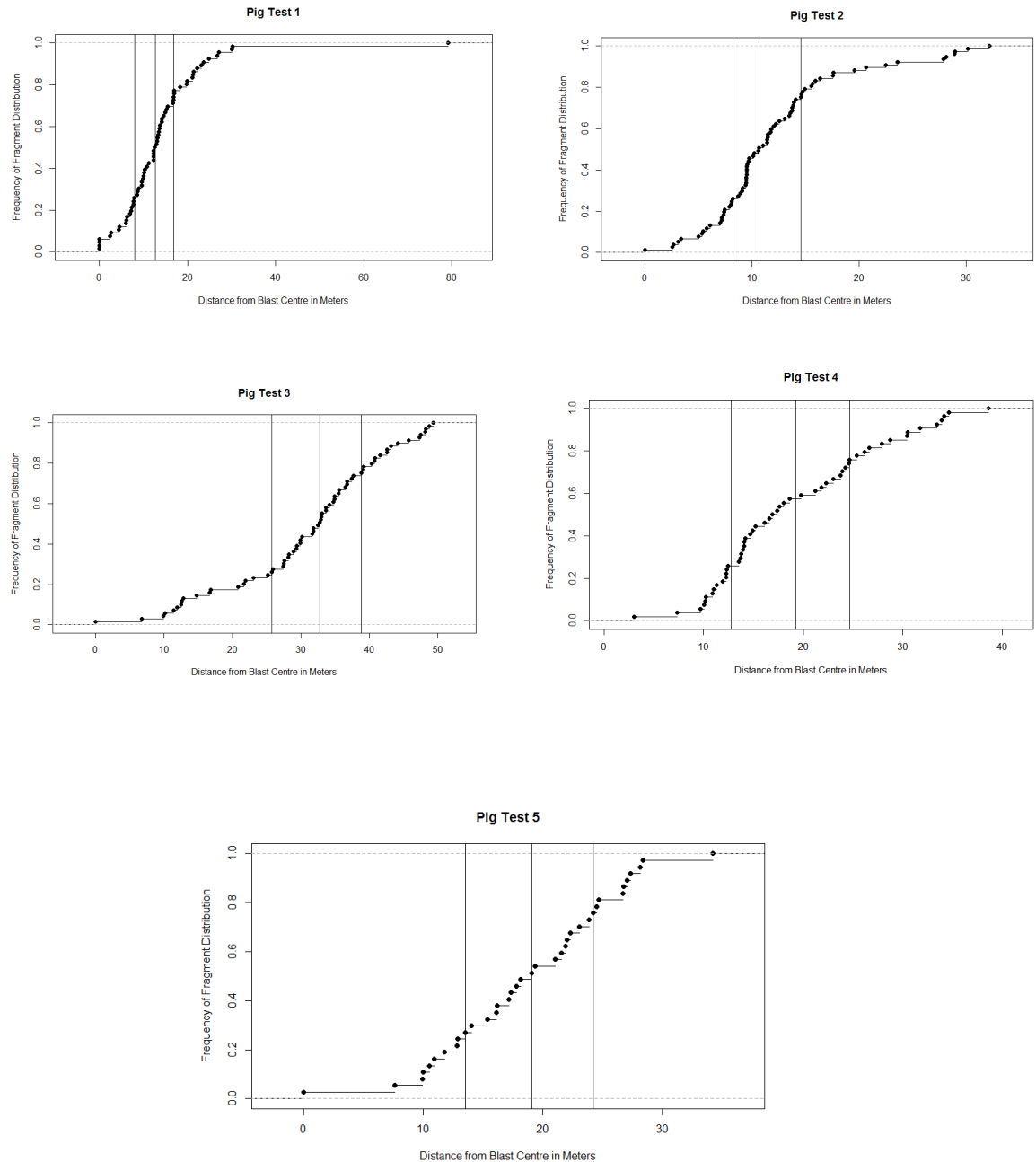
the blast. The fragments density increases slightly before decreasing as the distance from the blast centre increases. It should be noted that in test 3 and 5, the fragmentation peaks at a further distance than it does for the other tests.



**Figure 5.6.** The density bar charts from the piglet target data sets.

The cumulative density graphs were produced next (see Figure 5.7). The vertical lines present in the graphs represent the percentages of the fragments within the Q1,

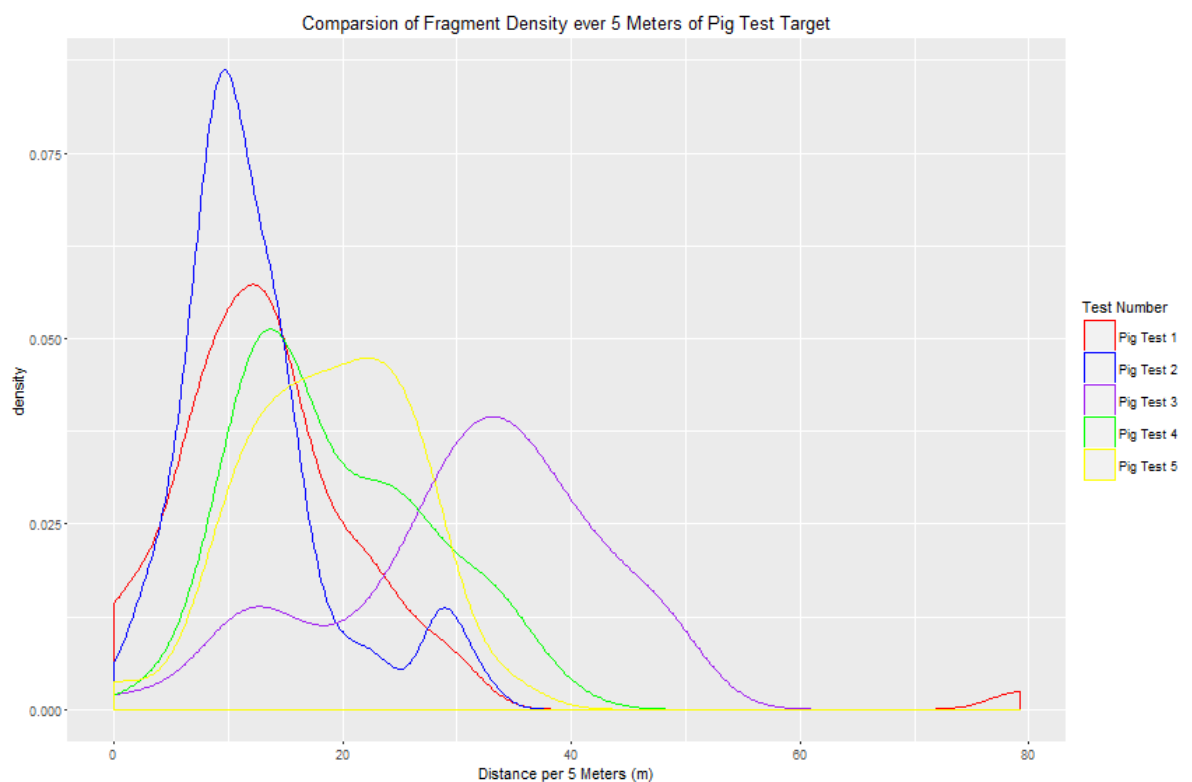
Median and Q3 respectively. Across all of the piglet tests, 50 percent of the fragmentation is observed within 30 meters of the blast centre.



**Figure 5.7.** The cumulative density graphs of the piglet target data sets.

Next, the cumulative density data (see Figure 5.8) from all of the five tests was graphed to identify the similarities and differences in the fragment density produced. Each colour represents a different piglet test and allows for a visual comparison of the

data. In each test, there is an initial peak in the fragment density near the spot of detonation before a decrease in that density. In test 3 (below in purple) and test 5 (below in yellow), the fragment density peaks at a further distance from the blast centre then the other three piglet tests. Both test 2 and 5 occurred at the same time and this further distance peak present in both test may have been caused by an unrecorded increase in the wind in that section of the quarry site. This would have helped increase the fragmentation distances and impact the distance from the blast centre of the fragmentation density peak. It could also have been caused by the location of the piglets on the quarry site in relation to the rock piles that surrounded the area. The blast wave in these instances may have hit the rock pile and refracted back into the area, increase the overall direction of the fragmentation. Another theory as to this difference could be linked to condition of the piglets prior to the explosions occurring. In these instances, the targets used for these two tests may not have been fully thawed and this would result in a different type of fragmentation distribution.

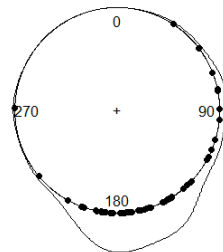


**Figure 5.8.** All of the piglet test density distribution compared to one another.

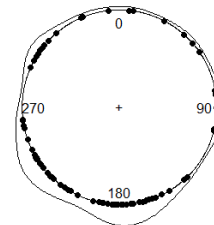
Circular statistics (see Figure 5.9) were then applied to the data set. This was done to examine the resulting directionality of the fragment spread. The degree to which the

majority of the fragments across all five tests can be directly traced back to the location and position of the explosive device placement on the target are shown below.

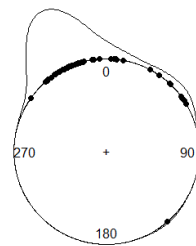
Circular Density of Fragment Distribution of Pig Test 1



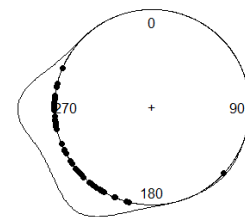
Circular Density of Fragment Distribution of Pig Test 2



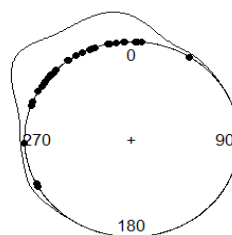
Circular Density of Fragment Distribution of Pig Test 3



Circular Density of Fragment Distribution of Pig Test 4



Circular Density of Fragment Distribution of Pig Test 5



**Figure 5.9.** The circular graphs of the piglet target data sets

Rayleigh's test of uniformity (see Table 5.1) was also applied to observe the directionality of the fragmentation spread. The results from this statistical test demonstrate that the spread was heavily impacted by the placement of the bomb on the

target and therefore the data is directional in nature. The p-value of  $p < 0.01$  indicated a rejection of the null hypothesis that the spatial data fell equally around the blast centre.

Test Number	Rayleigh's Test of Uniformity Result	P-Value
Pig Test 1	0.7818	$p < 0.01$
Pig Test 2	0.398	$p < 0.01$
Pig Test 3	0.8833	$p < 0.01$
Pig Test 4	0.832	$p < 0.01$
Pig Test 5	0.8539	$p < 0.01$

**Table 5.1.** Rayleigh's test of uniformity conducted on the data set collected from the scaled piglet experiment.

Lastly, a Watson-Wheeler test (Table 5.2) which demonstrates the high impact of location of the explosive devices had on the resulting spatial distribution, was performed. None of the tests show a p-value of .05 or higher, meaning across the experiments there was no similarity between the angles of highest fragmentation concentration. This indicated that in each instance, the explosive device was placed differently on the piglet targets, which produced different fragmentation distribution.

Test Number	Pig Test 1	Pig Test 2	Pig Test 3	Pig Test 4	Pig Test 5
Pig Test 1		26.17	102.8	81.13	72.58
Pig Test 2	26.17		93.22	25.87	51.03
Pig Test 3	102.8	93.22		96.26	15.31
Pig Test 4	81.13	25.87	96.26		51.66
Pig Test 5	72.58	51.03	15.31	51.66	

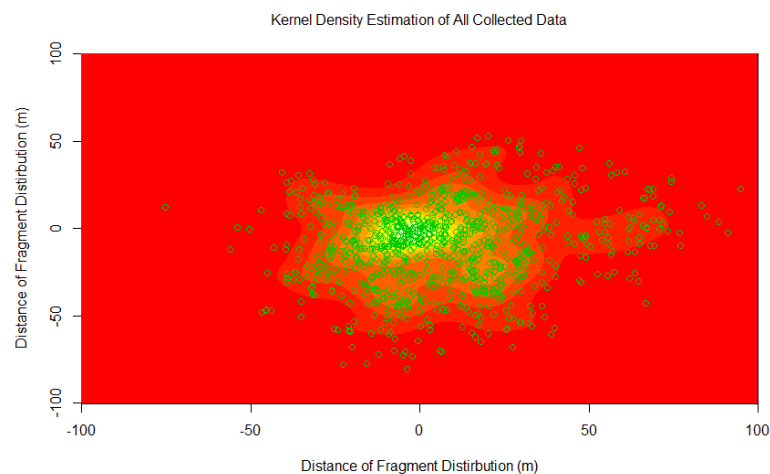
p-value < .05

**Table 5.1.** The Watson-Wheeler test results from the piglet experimental data,

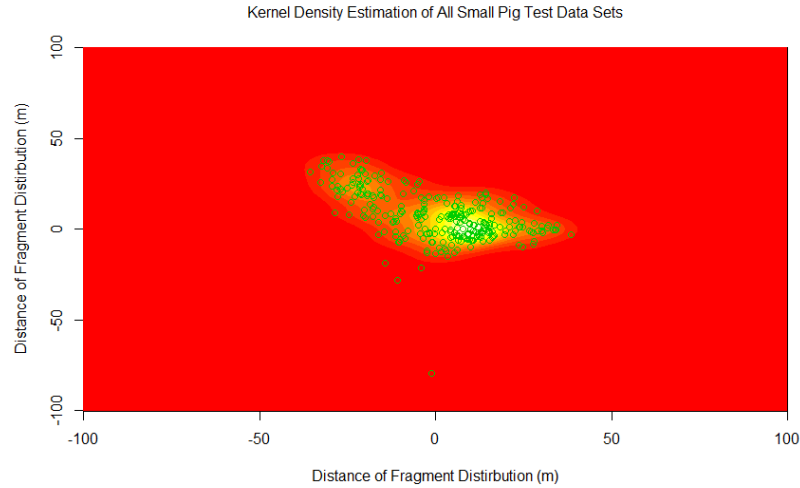
In summary, the results produced by the piglet data were highly directional in nature, with the fragmentation clustering at/near the blast centre. In terms of fragmentation density, test 3 and 5 presented some outliers in the data set as they tended to have peaks of fragmentation further away when compared to test 1, 2, and 4. This may have been caused by environmental factors, blast wave refraction or the condition of the target tissue. Following the individual statistical tests described here, a series of comparison tests with the previous acquired Large Pig dataset was undertaken.

#### 5.4 Analyzing the general similarities and differences between the large pig and scaled piglet tests

Since the target tissue (i.e. pigs) used in the two sets of experiments were the same, it is not surprising that there would be similarities between the two sets of data. One of these similarities is that at or near the centre of the blast a majority of the fragments from both sets of experiments were located (see density bar graphs Figure 5.6; DuBois *et al.* 2017 and Appendix A). The similarity between the two data sets is also observed in the collective kernel density estimations (KDE) (Figure 5.10 and Figure 5.11). In both experimental data sets the majority of the fragmentation is recorded at/near the centre of the blast and as the distance from the blast site increases the density of the fragmentation decreases.



**Figure 5.10.** The KDE plot which shows all of the large pig test data rotated and lined up to show the collective spread of the fragmentation. As noted above the majority of the fragments are recorded at/near the blast centre.



**Figure 5.11.** The KDE plot of the combined data set of the scaled piglet tests. All of the collected data has been rotated and lined up on top of each other to show the overall collective data set. Once again, the majority of the fragmentation is located at/near the blast centre.

The impact of the placement of the explosive device and the resulting fragmentation distribution is another similarity between the two experiments. Although the explosive amount differed, the placement of the device directly impacted the overall spread of the fragmentation. As noted in the circular distribution (Appendix A) for the large pig experiment and in Figure 5.9 for the scaled piglet data, the results are highly directional in nature. This directionality is specifically tied to the placement of the device on the target and resulted in the highest concentration of fragmentation falling within a certain angle range. This directionality in both cases is further highlighted in the Rayleigh's Test of Uniformity (Table 5.1 for the scaled piglet tests; DuBois *et al.* 2017 and Appendix A for the large pig tests), which demonstrated that in both series of tests they firmly rejected the null hypothesis that the fragmentation created in the blast event fell evenly around the blast centre. Furthermore, the Watson-Wheeler results (Table 5.2 for the scaled piglet tests; DuBois *et al.* 2017 and Appendix A for the large pig experiment) support this by demonstrating that there was dissimilarity in the direction of blast angles between all of the recorded sets of experiments.

This dissimilarity in blast angle direction may be due to two separate factors. In the case of the large pig experiments, due to the difficulty in getting the pig upright onto the wooden stakes, it was decided to use whatever direction was possible to hold the pig in place long enough to secure it for the duration of the test. This mean that although the placement of the device was kept constant (directly on the centre chest of the pig), the

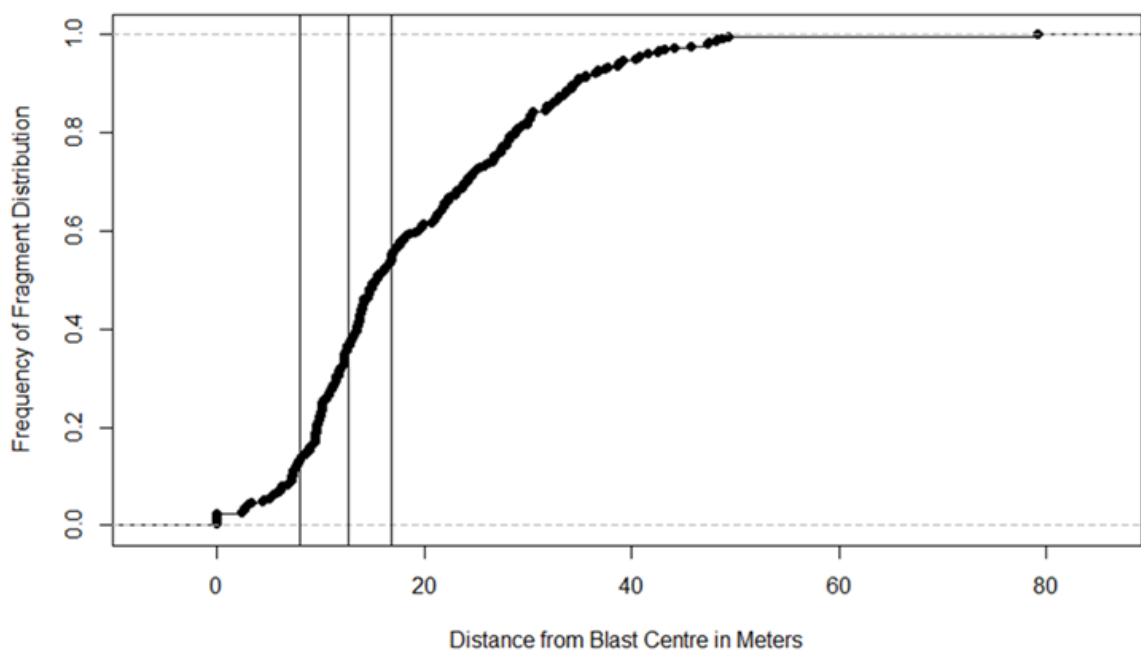
direction of the blast angle differed. In the case of the scaled piglet experiments, the distance from the blast location to the position where the blast was ignited was too great for the use of wire. This meant that radio frequency was employed, which increased the danger of premature blast occurring. Any radio wave could interfere with the test and cause the blast to occur while a member of the team was still on or near the blast site. For this reason, the researcher was not allowed to be present at the blast site while the charge was put in place. Although specific instructions on where the explosive was to be placed, the reliability of this cannot be verified. Although there are differences in the blast angle, what the results do indicate is the high sensitivity to a small variation in the placement of the explosive device on the target in relation to the resulting fragmentation distribution. While the methodology was kept the same between the two sets of experiments, the similarity in results make sense. The explosive and the primer charge were placed similarly between the two sets of experiments. This meant that the direction of the explosive force into the tissue target was the same in both instances. With this similarity of force directionality applied to the same type of biological tissue, the resulting fragmentation should be similar in both cases.

Although the tissue targets for both of the experiments were the same, several differences between the two experiments can be identified. One of the major differences is that the scaled experiments produced overall smaller maximum distance when compared to the full size pigs. In the case of the large pigs the mean maximum distance was recorded at 76.5 meters and the mean maximum distance for the piglet was recorded at 53.92 meters. As the scaled pigs used only  $1/6^{\text{th}}$  the explosive amount that was employed during the full size experiments, the difference in the maximum distance obtained by the two sets of experiments is to be expected. As previously noted, the full size experiments employed a higher amount of explosive. The obvious result was that more explosive force is applied to a larger amount of tissue, resulted in a greater chance of fragments travelling further. More data is needed, however, to provide an indication of how well the scaling laws that are used to determine scaled explosive maximum distance are applicable to determining scaled tissue fragmentation maximum distance.

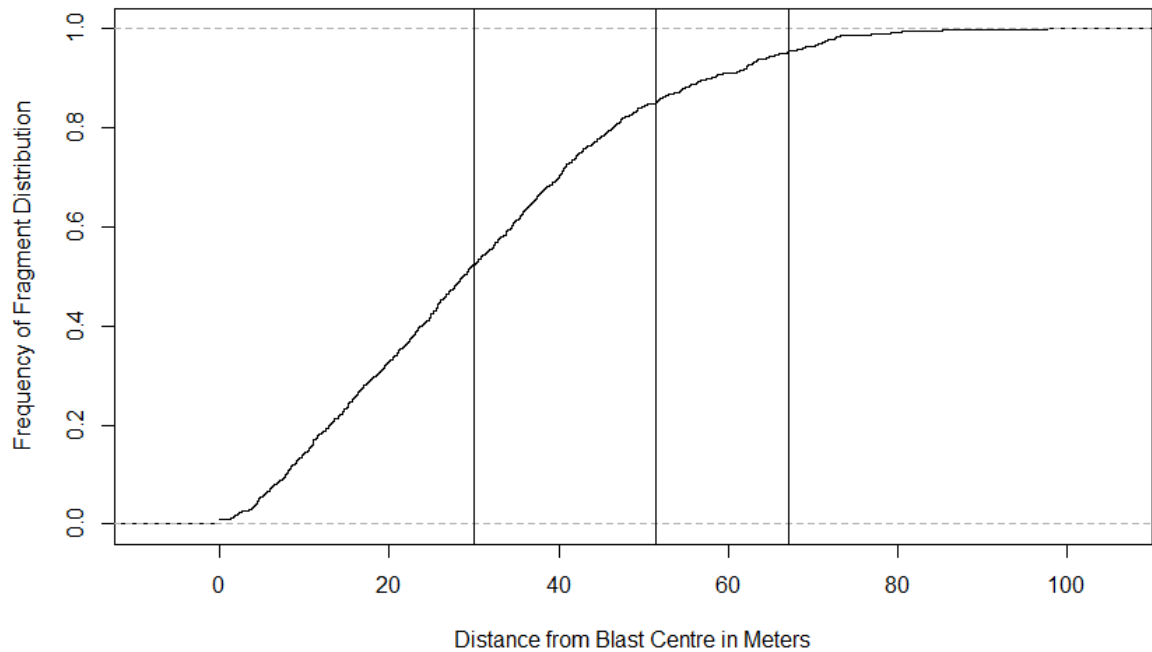
Another difference between the two sets of experimental data is the location of percentages of fragments. In the case of the scaled piglet data set (see Figure 5.12), the location of the 25, 50, and 75 percent of tissue fragments are clustered within a similar distance range across the tests. This is different from the full size experiment (see Figure



5.13), where the location of the 25, 50, and 75 percent of the tissue fragments among the different tests are more spread out when compared to each other. One explanation for this difference is that the scaled experiments have the explosive force acting on a smaller area of tissue when compared to the tissue area of the full size experiments. With less tissue to act on, this could result in more clustering of the fragmentation. In the case of the full size experiments, the explosive force is acting on a larger area of tissue. This creates more fragmentation compared to the scaled tissue experiments, likely resulting in a larger fragment spread. This meant that the fragmentation produced is more likely to be more spread-out due to the higher explosive force. Another factor in the location of the percentage of the fragments could be the environmental conditions in which the two experiments were conducted. The large pig experiments were conducted in a very wet, windy and cold environment, where the scaled pig experiments were conducted on a hot and humid day with very little wind present. The range that was employed for the large pig experiments was also a wide open field, meaning the presence of the high wind speed could have had an influencing factor on the resulting fragmentation. The impact of weather conditions on the maximum distance obtained by the explosive chemical components along with the overall distribution has been noted in other forensic experiments (Abdul-Karim et al 2016). It is not surprising that this impact could also be tied to the tissue fragmentation created in an explosive event.

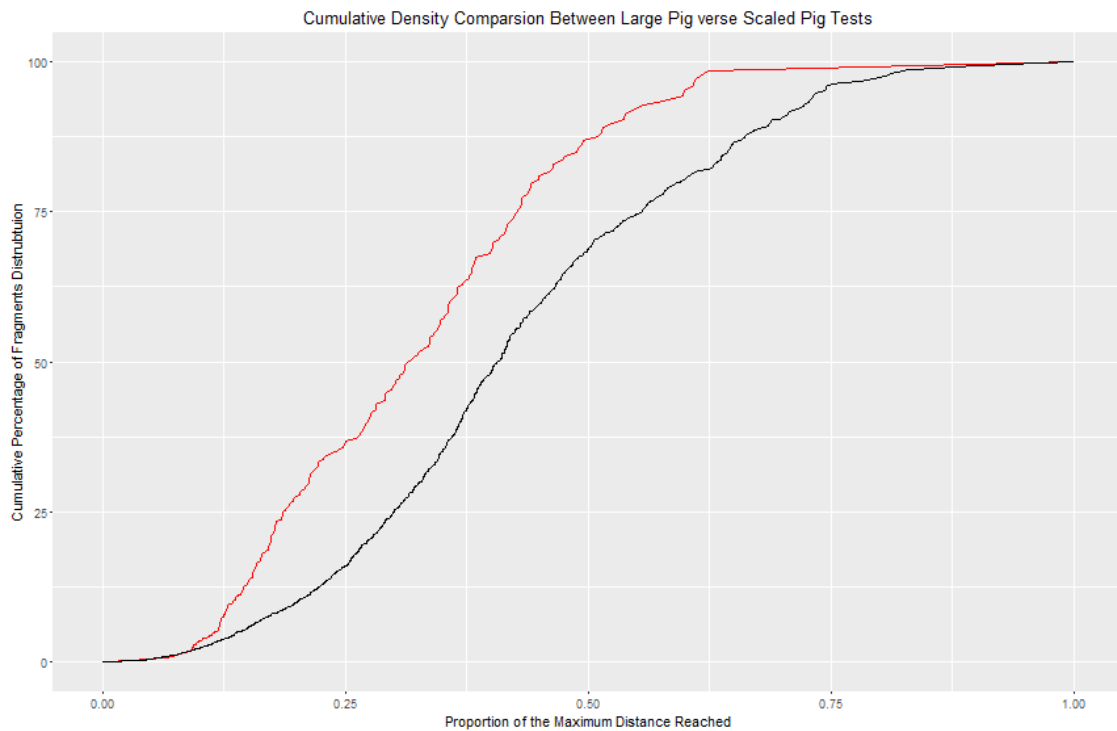


**Figure 5.12.** The cumulative density graph of the scaled piglet fragmentation spread. The lines represent where the Q1, Median and Q3 percent of the fragments landed.



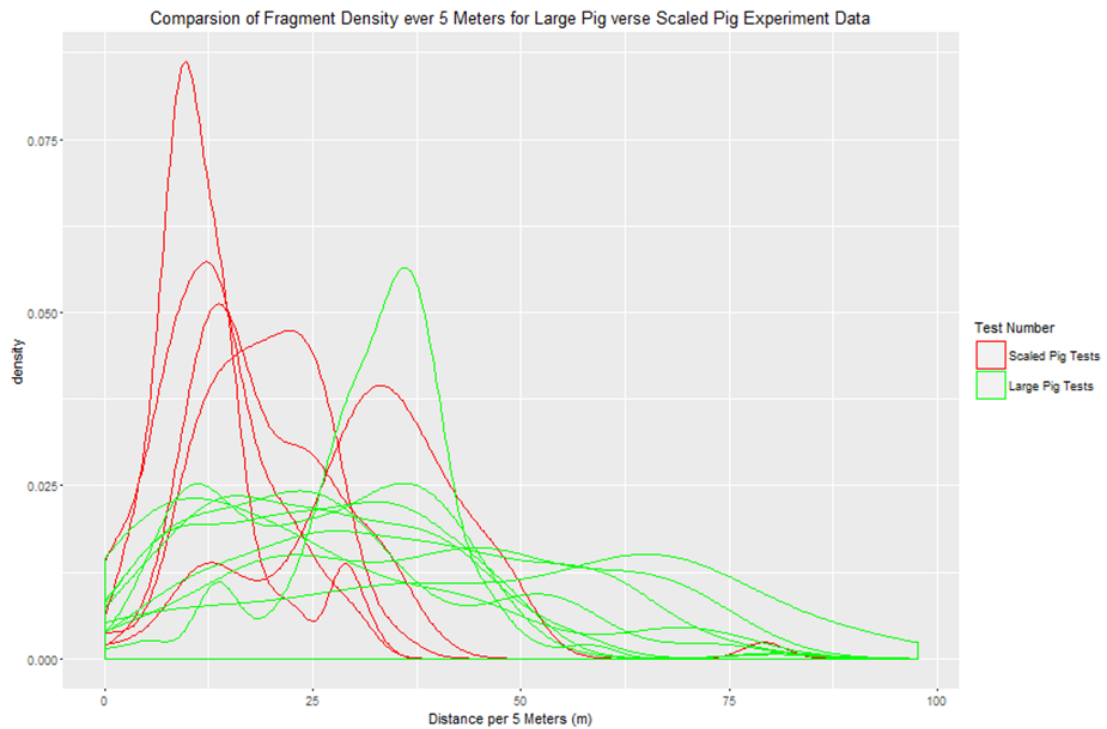
**Figure 5.13.** The cumulative density graph of the full size pig fragmentation spread. The lines represent where the Q1, Median and Q3 percent of the fragments landed.

The difference between the two experiments was further demonstrated by examining the shape of the cumulative fragment density distribution (see Figure 5.14 for the comparison graph), which again differed notably. The comparison was achieved by examining the proportion of the maximum distances by the related percentage of fragment distribution. This allowed for the difference in size of the pigs to be removed and to purely compare the shape of the fragment distribution between the two experiments. The resulting graph demonstrates that the scaled piglet tests (in red) are very dissimilar from the large pig tests (in black). This is supported further when examining the results of the KS test ( $D = .34$ ,  $p < 2.2e-16$ ), which also indicate that the data sets were different from each other.



**Figure 5.14.** The cumulative density comparison between the scaled pig experiments (in red) and the large pig experiments (in black).

These differences in the two data sets are also observed in Figure 5.15, in which the shape of the fragment distribution is clearly very different between the two experiments. The scaled pig fragment distribution (represented in red on the graph) has a higher concentration of fragmentation closer to the blast centre when compared to the large pig data set. This difference may be caused by how the scaled pigs were stored before they were used. All five piglets were stored in a freezer and all attempts were made to ensure that they were fully thawed. However, due to the high temperatures that occurred the day of the experiment the test on the targets needed to be conducted right away. This was done to prevent any sort of decomposition that would have occurred if they had been tested later during the day. If the scaled pigs were still partly frozen (internally) then this may have impacted how the tissue fragmented as a result of the explosion. In the high speed video taken of the very first scaled pig test demonstrated that the impact of the tissue partially being frozen may have been the reason behind the test outcome differences. A major section of the piglet which includes the head and portion of the torso, was observed leaving the blast centre as one large single fragment. Since this was the first scaled pig that was tested and if the tissue was not fully thawed, then this could have an impact on the overall fragment distribution.



**Figure 5.15.** The comparison of the fragment density between the large pig experiments and the scaled piglet experiments.

## 5.5 Conclusion

There are a number of similarities and differences between the data produced by the experiments using full sized pigs and piglets. They are similar in terms of the shape of the fragment distributions and the directional nature of the explosive force. The major differences were in terms of the cumulative fragmentation density distribution and the distance location of the fragmentation density. The methodology used in both cases was the same, along with how the data was processed and analysed. However, there were known contextual differences such as the weather and the temperature of the targets. This gives mixed evidence, and may indicate that scaling the targets is not a viable avenue for conducting this type of forensic experiment and that other methods need to be explored. This is further explored in the discussion chapter.

## **Chapter Six. Large Pig Test versus Large Gelatine Test**

To further un-pick the issue of material viability, additional experiments were conducted using large ballistics gel blocks. This was undertaken to determine whether this cheap, easy to obtain/use material was a sensible and viable alternative to large pig carcasses. The use of the gelatine was actually suggested by the law enforcement practitioners as a possible means of a target material substitute as they often use this material within their departments to do firearms exercises. A large gelatine block was tested and the results compared to the data collected during the large pig tests to observe if this target material is a useful comparable material to biological tissue. This section of the PhD research once again took place with the assistants of the Montgomery County Sheriff's Office EOD team of Pennsylvania and were conducted at a range located outside Leesport, Pennsylvania. The equipment (the gel block and total station) was delivered to the hotel the researcher was staying at. On the day of the test the researcher and all of the equipment were driven to the site by a member of the EOD team.

### **6.1 Large gelatine test set-up**

Following the basic methodology that was discussed in the methodological chapter (see section 3.1), the single gelatine torso was placed in the middle of the quarry site (see Figure 6.1) with the block of C4 weighting .68 kgs placed directly on the centre front of the block (See Figure 6.2). This experiment was conducted at a quarry site (see Figure 3.7) where the temperature was recorded at a high of 17 degrees Centigrade and a wind speed of 8 kilometres per hour in a south/south-westerly direction.





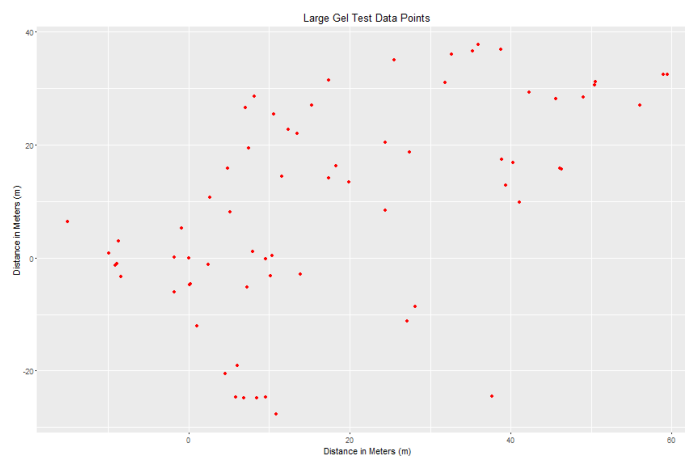
**Figure 6.1.** A photograph showing the quarry site that was employed to test the single gelatine block and the noted low cloud ceiling that was one of the factors that led to the decrease amount of explosive material.



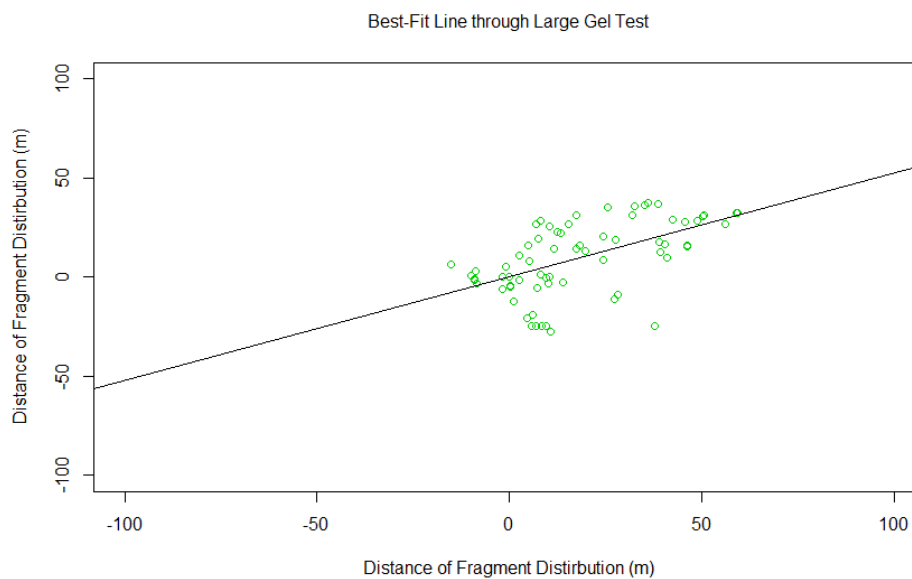
**Figure 6.2.** The large gelatine block with the .68 kgs of C4 explosive (a US Imperial weight measuring unit was employed; 1.5lbs was the weight in pounds) placed directly onto the middle of the target.

## 6.2 Large gelatine results summary

The collected data was then uploaded onto the researcher's computer and then run through the R studio statistical program. The results obtained from that program are presented below. As described in greater detail in the methodology chapter, the data was first run through the R program to produce a best fit line in which all of the data points were tied to their unique spatial location (see Figure 6.4). Like previous experiments, the resulting fragmentation spread was directional in nature, moving out and back from the centre of blast.

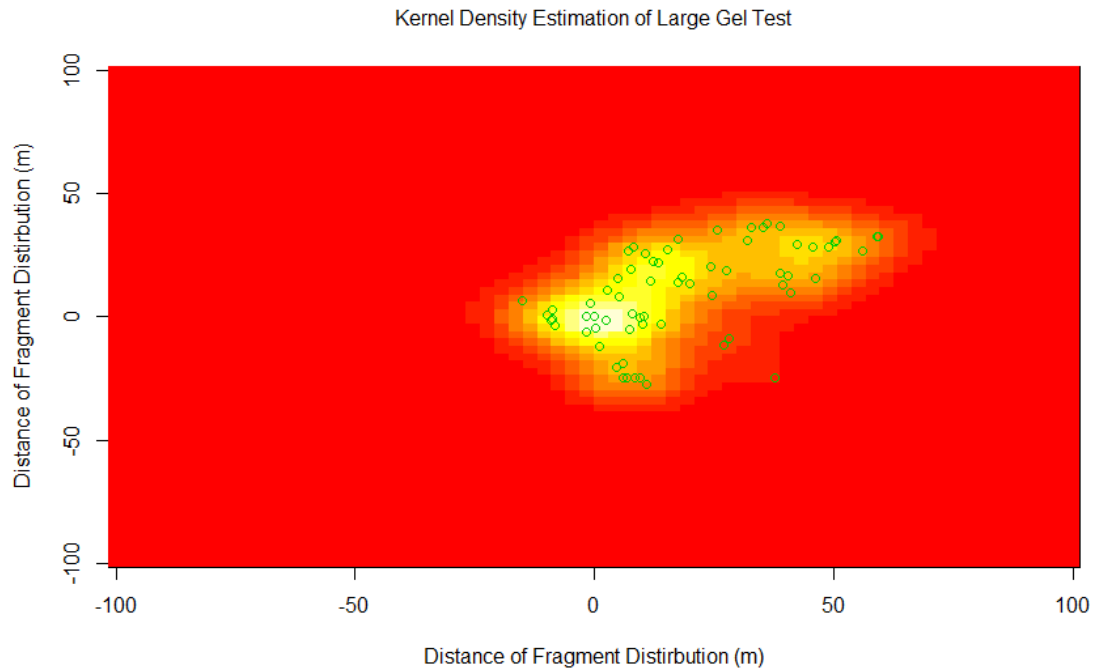


**Figure 6.3.** The overall spread of the fragmentation created after the detonation of the large gelatine block.



**Figure 6.4.** The linear regression graph which indicated the line of best fit for the data set of the large gelatine block.

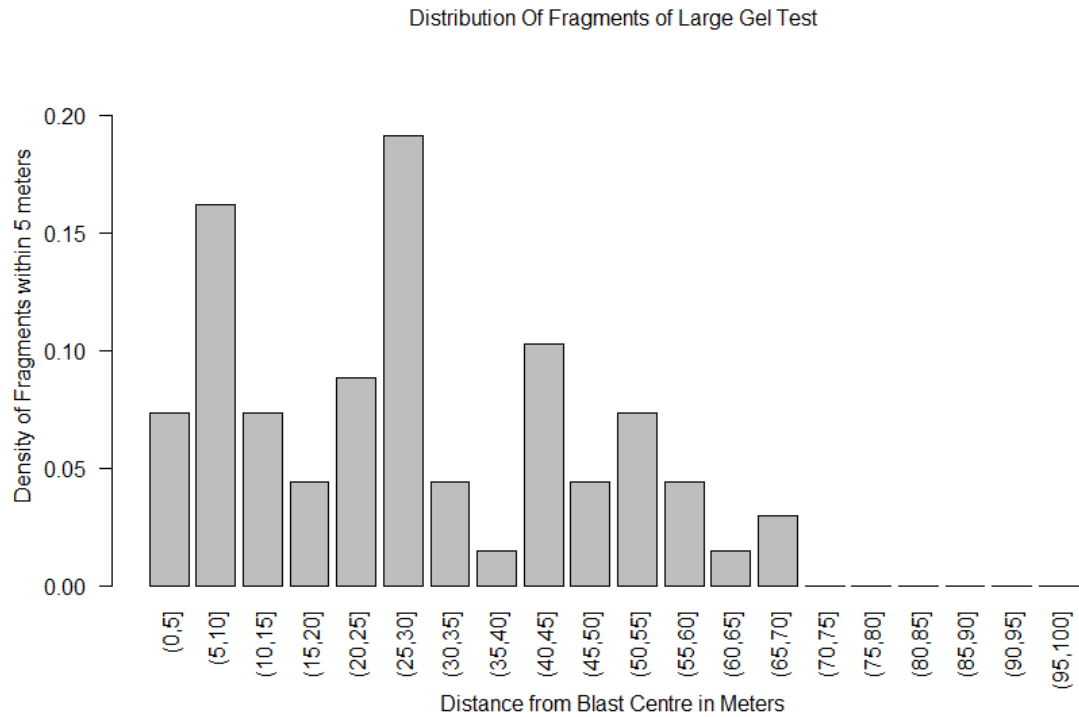
Next a KDE plot (Figure 6.5) was produced and once again, the directionality of the spread should be noted along with the overall clustering of the fragmentation at/near the blast centre.



**Figure 6.5.** The KDE graph of the large gelatine fragmentation spread.

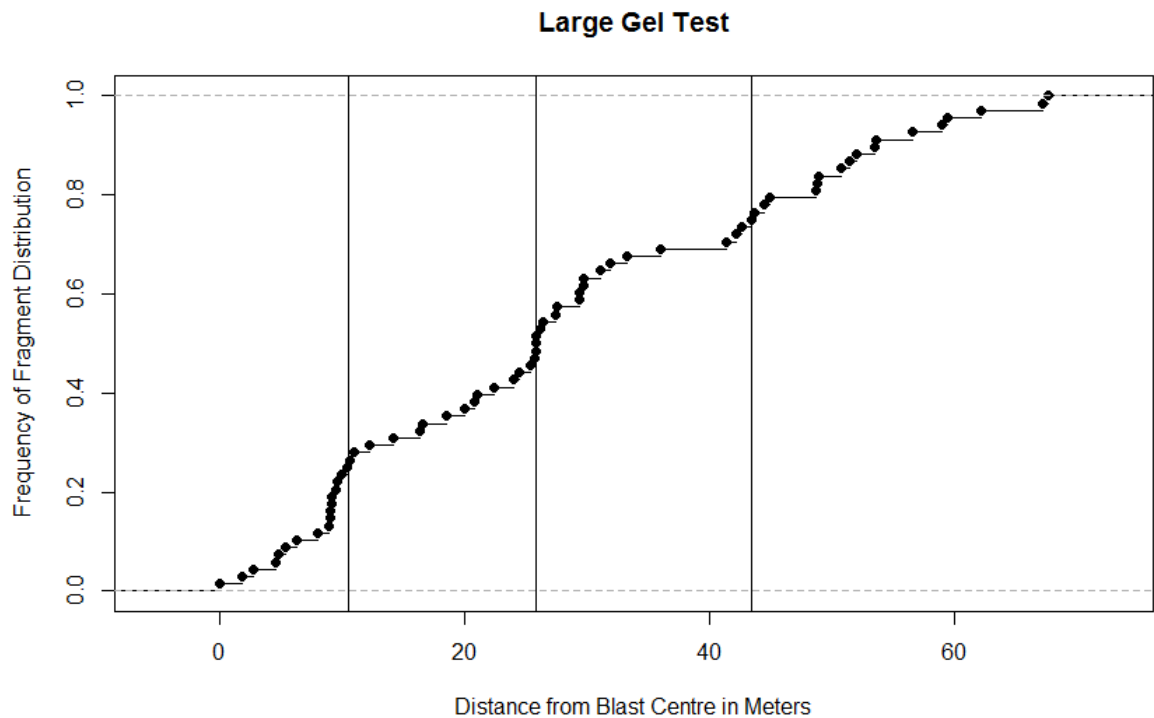
A density bar graph (Figure 6.6) were produced to identify the overall fragmentation spatial patterning. The majority of the fragmentation landed at or near the centre of the blast site, with most falling within 30 meters of the blast centre.





**Figure 6.6.** The fragment density distribution of the spread of the large gelatine block.

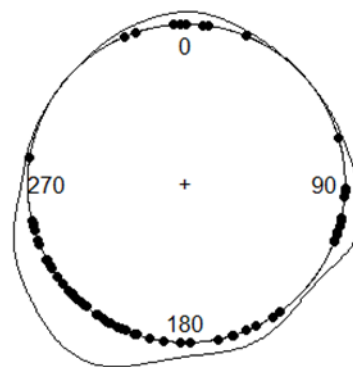
A density distribution data was next produced (Figure 6.7) to identify the fragment percentage found at certain distances from the blast centre. The frequency of the distribution of the fragmentation marked out at the 25, 50, and 75 percent amounts. Most, if not all of the fragmentation fell within 50 meters of the blast centre.



**Figure 6.7.** The frequency of the large gelatine fragmentation.

Next a circular statistics (Figure 6.8) was applied to visually observe any directionality present in the data set. Once again, like the best-fit line in Figure 6.5 the directional nature of the data set is visually demonstrated with the majority of the fragmentation falling between 270 and 180 degrees from the blast centre.

Circular Density of Fragment Distribution of Large Gel Test



**Figure 6.8.** The circular distribution graph of the large gelatine block.

Lastly, Rayleigh's Test of Uniformity was employed to identify any sort of directionality present in the fragmentation spread. This produced a test statistic of .4761 with a  $p$ -value of 0, indicating a data set that is directional in nature. A Watson-Wheeler test was not performed as there were no other large gelatine blocks that were tested to compare and contrast with each other. Overall the spatial data that was produced by the single large gelatine block was directional in nature (in relation to the placement of the explosive device), with the fragmentation clustering around/ near the blast centre. The density of the fragmentation increased slightly moving away for the blast centre before decreasing. Following this was the series of tests described in Chapter Four that allowed closer statistical comparison of the large pig and large gelatine sub-groups of data which is reported in section 6.3.

### **6.3 Comparing the experimental results from the large pig experiments and the large gelatine block test**

In examining the statistical data produced by the R program (discussed in great detail in Chapter Four), several observations were evident between the large pig experiments (see Appendix A) and the large gelatine block. The resulting spatial distribution in both instances can be described as clustering around the blast centre and the fragmentation decreasing as the distance from the centre increases. This clustering can be observed in the density bar graphs (see Appendix A for the large pig data in Figure A6 and Figure 6.6 for the large gelatine data), which show that in both instances 25 percent of the fragmentation was collected before or around the 20 meter mark from the blast centre. This clustering pattern is further observed in the resulting KDE plots (DuBois *et al.* 2017 and Appendix A for the large pig experiments in Figure A5; Figure 6.5 for the large gelatine experiments). This is reflected in the majority of the fragmentation (represented in the bright yellow colour) falling around and near the blast centre.

This clustering aspect that is present in both experiments is most likely related to how the blast wave interacts with the overall environmental air pressure. As discussed in greater detail in section 2.4, the chemical reaction that produces the blast wave dissipates fairly quickly. This lack of blast wave power means that the resulting fragments can only travel so far before their velocity ends. Another aspect of the blast wave that would impact the fragmentation spread and the clustering patterns is the resulting vacuum that occurs. As the blast wave moves away from the blast centre, the environmental air pressure increases. This increase in environmental air pressure decreases below normal levels in an attempt to stabilize, and creates a vacuum in which any debris created by the initial explosions can then be dragged back towards the centre. The combination of both the lack of staying power of the blast wave and the resulting vacuum therefore produces the observed clustering of both experiments.

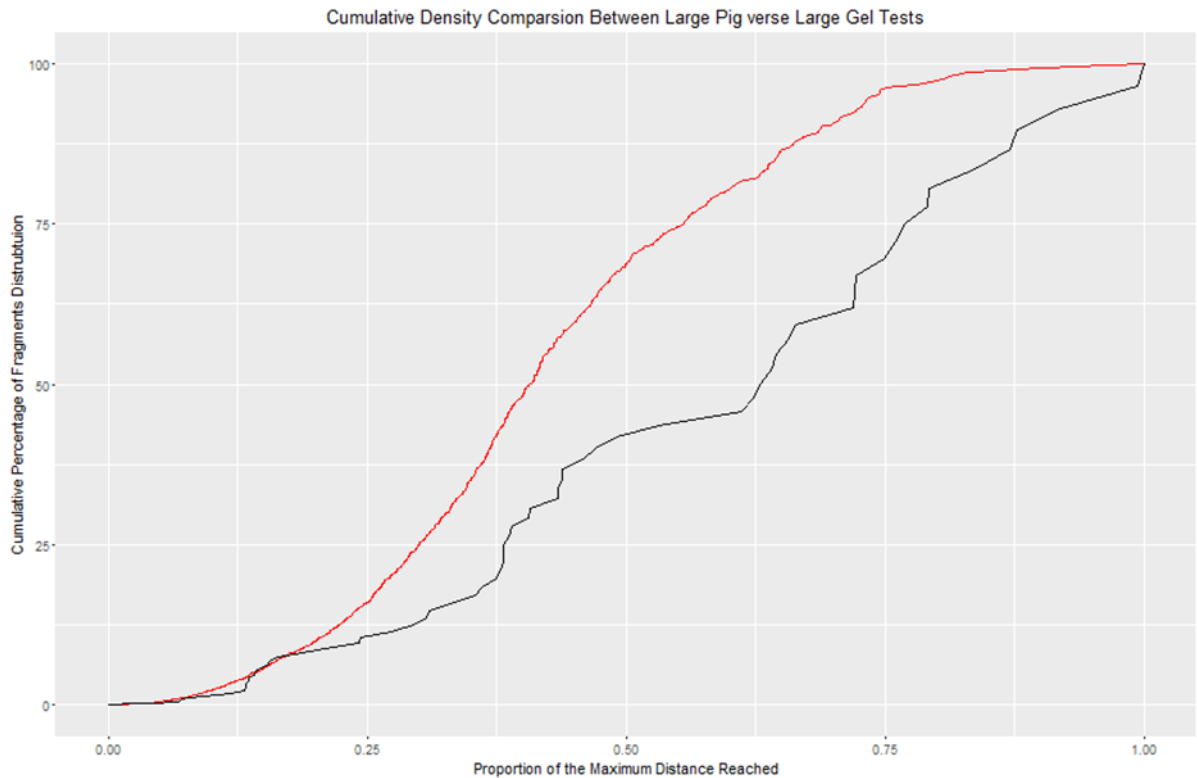
The impact of the placement of the device on the fragmentation spread was also observed in the statistical results. In circular statistics (see DuBois *et al.* 2017; Appendix A7 in Figure A; Figure 6.8), the highest concentration of the fragments fell within a specific angle range which is directly related to the placement of the device on the targets. Once again, the Rayleigh's Test of Uniformity for the large gelatine experiment produced

a test statistic of .4761 with a p –value of 0, which was similar to the Rayleigh’s tests conducted for the large pig experiments which also indicted a data set that was highly directional in nature (DuBois *et al.* 2017 and Appendix A in Table A2). In both cases, the null hypothesis of an equal distribution around the blast centre was rejected. In the case of the large pig experiments, there is variation between the angle range in which the fragmentation falls. This is due to the challenges associated with getting the pigs in an upright position on the wooden stakes. As soon as the pig was in an upright position, it was immediately tied to the post, no matter the direction the centre front of the chest was pointing. This produced the range of angles which can be observed in the circular statistics located in Appendix A (see Figure A7).

The maximum distance obtained in the case of the large gelatine block barely exceeded 60 meters, while the average maximum distance of the large pig experiment was 76.5 meters. This difference between the two data sets can be further observed in the fragmentation density distribution (DuBois *et al.* 2017 and Appendix A for the large pig experiment in Figure A8; Figure 6.6 for the large gelatine experiment). In the case of the large pig experiments, 50 percent of the fragmentation is recorded prior to the 50 meter mark. With the large gelatine experiment, this same percentage of fragmentation is recorded within the 30 meter mark. Although not similar to each other in each of the above aspects, the large pig experiment was conducted with a full 3 kgs of explosives when compared to the .68 kgs used for the large gelatine experiments (explained in section 6.2). Another factor that would impact the maximum distance of the fragmentation spread is the weather. As discussed earlier in Chapter Five and in Appendix A, the large pig experiments were conducted in weather that was wet, cold, and very windy (the highest recorded wind speeds were recorded between 25 and 30 mph). As noted in Abdul-Karim *et al.* (2016), weather has been noted as impacting the maximum distance that the explosive chemical particles are recorded. The high winds speeds having an impact on the maximum distance of the large pig experiment data sets would not be out of the ordinary. The combination of the decreased size of explosive in place during the large gelatine experiment and the high wind speed present in the large pig experiments may have played a role in the differences in the overall fragmentation distribution.

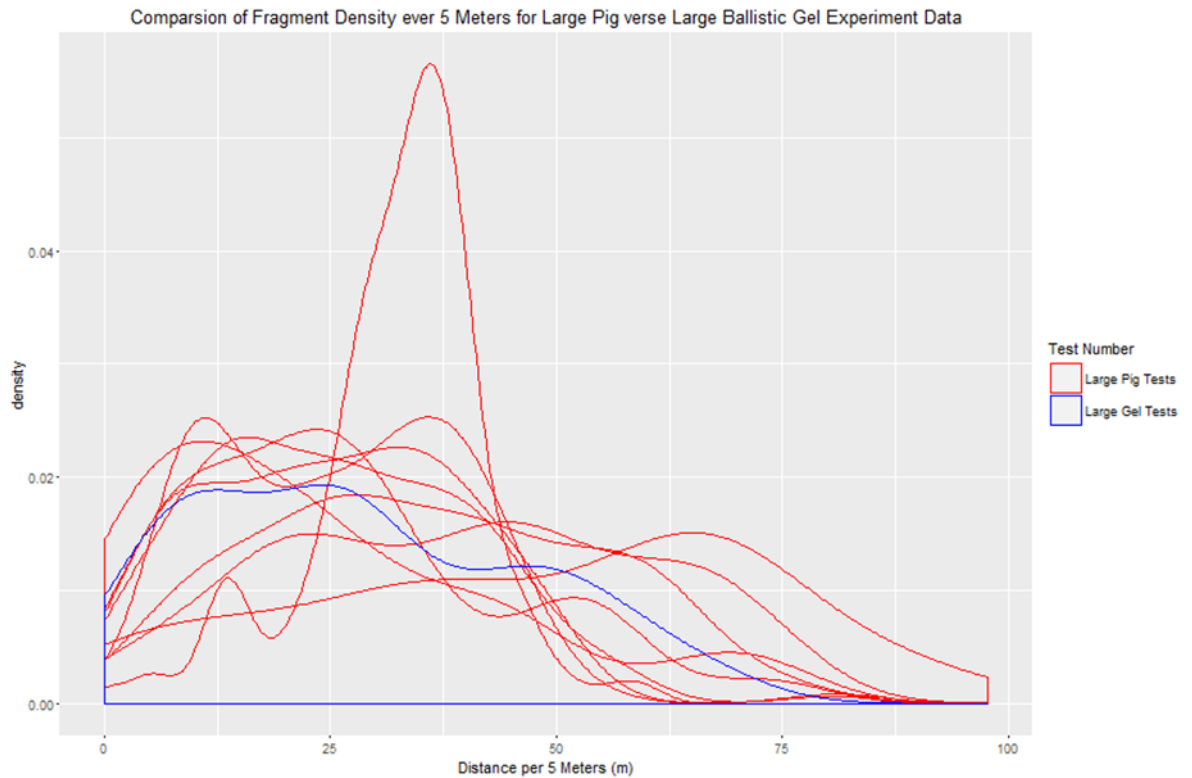
Another difference between the two data sets that should be noted is highlighted in the cumulative density comparison graph (see figure 6.9). The large pig experiment (in

red) having a higher cumulative density of fragment percentage at an equal distance from the blast centre when compared to the large gelatine experiment. Within the first 25 percent of the maximum distance obtained in both test, the cumulative percentage is fairly similar. This similarity ends after this percentage of the maximum distance obtained.



**Figure 6.9.** The comparison graph which examines the cumulative percentage of both the large pig data set (in red) and the large gelatine test (in black) fragmentation based on the proportion of the maximum distance reached.

When the fragmentation density between the two data sets was compared (see Figure 6.10), the large pig experiment had a higher fragment density per five meters when compared to the large gelatine experiment. The data for both experiments has a general peak at or near the blast centre before decreasing as the distance from the blast centre increases. The large pig experiment data, however, demonstrates on average a higher density of fragmentation per five meters when compared to the large gelatine fragmentation distribution over the same distance. This fragmentation distribution is further reflected in the resulting KS test ( $D=.144$ ,  $p\text{-value}=.135$ ), which indicates that the comparable data was produced by different experiments.



**Figure 6.10.** The comparison of the fragment density every five meters for both the large pig experiment data (in red) and the large gelatine experiment (in blue).

One reason for this difference in overall shape distribution may be simply due to the fact that two different material types were tested. As discussed in greater detail in section 2.5.2, gelatine is comprised of modified silicone which reacts to impact force in a similar manner to biological tissue. However, an explosive force is different from an impact force, as it forces the objects away from the centre of the blast rather than simply pushing down on an object. This means that whilst gelatine is an excellent model for how tissue reacts to certain types of force (gun shots), it is not necessarily a perfect fit for all situational forces that a biological tissue may undergo. The difference in fragment density is also likely to be due to difference in the nature of the materials being tested. The two target types, biological and gel, are made of different materials on a microscopic level and therefore are laid out differently. This difference in both material type and material construction means that the two tissue targets react very differently to the blast force. This is reflected in how the fragments disperse out from the blast centre. The gelatine is known to burn when exposed to ballistic trauma (Carr *et al.* 2018) and it may be that the any fragments that would have been located at/near the centre of the blast encountered a high enough heat that melted them away. This would explain why the fragments that were recorded on the total station were located at a further distance from the blast centre; these

fragments would have experienced less of the heat that is produced right at the site of the explosion, and so continued in the same fashion as the biological material. This lack of gelatine fragmentation located at/near the centre of the blast means that the overall fragment density distribution is different from the biological tissue of the pig which was able to withstand the initial heat of the explosive blast. The large pig experiment data, however, demonstrates on average a higher density of fragmentation per five meters closer to the blast when compared to the large gelatine fragmentation distribution over the same distance.

#### **6.4 Conclusion**

In conducting the large gelatine experiment, several set-backs were encountered. The first was that the anticipated explosive amount of 3 kgs to have a direct comparison to the large pig experiment was not able to be used. This was due to a cloudy weather which lowered the cloud ceiling, making the noise from the test travel further and the restrictions on blast weight present at the range that was employed. The second set back was that only one single large gelatine block was tested. This was due to the costs associated with the purchase of the gelatine block. In order to gain a true understanding of how reliable the large gelatine block is when compared to the large pig experiments, more experiments would need to be conducted and at similar explosive levels.

## **Chapter Seven. Scaled Piglet Test versus Scaled Gelatine Test**

This chapter describes research which aims to address the previously stated goal of enabling the development of a forensic evidence base of the behaviour of biological tissue fragments by testing the validity of using highly reproducible and cost effective substitute experiments. As stated previously the difficulty that often comes with obtaining biological tissue and the challenges of using a large amount of explosive, in this chapter alternatives to both were explored. This was done by both scaling the experiments to a 1/6<sup>th</sup> scale (in both explosive amount and tissue target) and using non-biological gelatine. The results described here are distinct from other chapters because they compare the behaviour of the scaled gelatine to the scaled biological targets (piglets). Ten tests were conducted in total and all experimental work was undertaken on the same day. This ensured they were conducted under similar environmental conditions.

### **7.1 Piglet mapping results**

The experimental process and subsequent analysis for the piglet tests are described in more detail in section 5.3, but the overall results discussed in this section demonstrated that the piglet fragments followed several aspects. The first is that like the large pig fragments, the data does not conform to a circular distribution which demonstrates the directionality of the blasts. The second is that the majority of the fragmentation is located at or near the centre of the blast site, which was similar to the large pig experiment data. Several of the results, however, were dissimilar from the large pig experiments. One of these dissimilarities is that although both of the experiments used real tissue targets, the total distance obtained by the piglets was much less than the large pig experiments, due to scaling. The second dissimilarity is that the location of the 25, 50 and 75 percentages of the fragments were different between the two experiments, with the piglet percentages falling much closer to each other than the large pig experiments. The last dissimilarity between the two experiments is that the overall fragment distribution



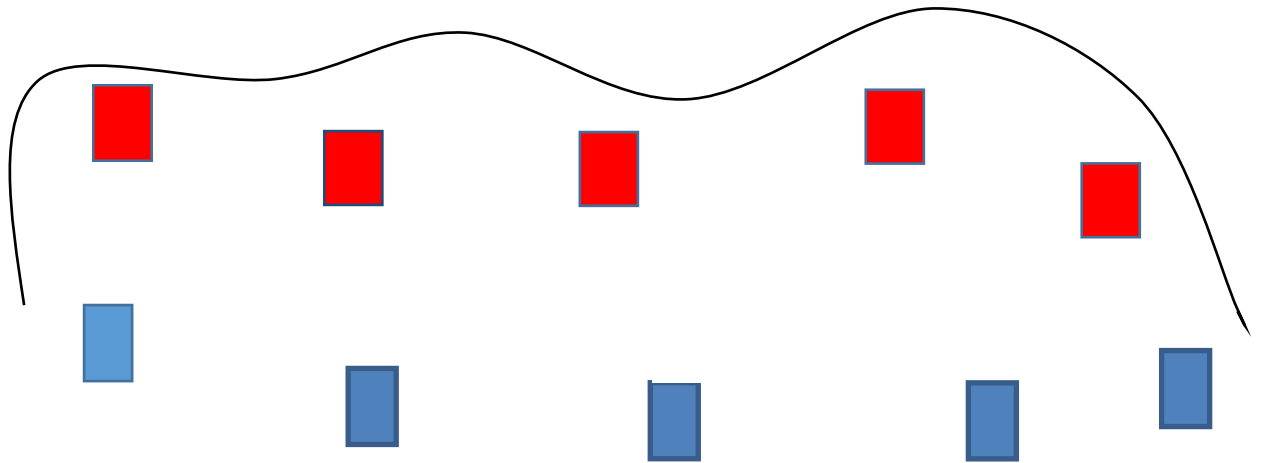
shapes in the piglet tests having a higher concentration of the fragments closer to the blast centre than the large pig experiments.

## 7.2 Gelatine experiment set up

After the completion of the piglet tests, all of the scaled gelatine tests were conducted. The five gelatine blocks (see Figure 7.1) were placed 30.48 meters away from each other (measurements were taken using an US Imperial measurement tape; 100 feet separated the gelatine) and 0.5 kgs of C4 explosive was placed directly on the front centre of the gel. This made the gelatine experiments directly comparable to the piglet, with the primary charge placed directly into the centre of the explosive charge to direct the majority of the force into the target. The location of the gelatine blocks can be observed in Figure 7.2.



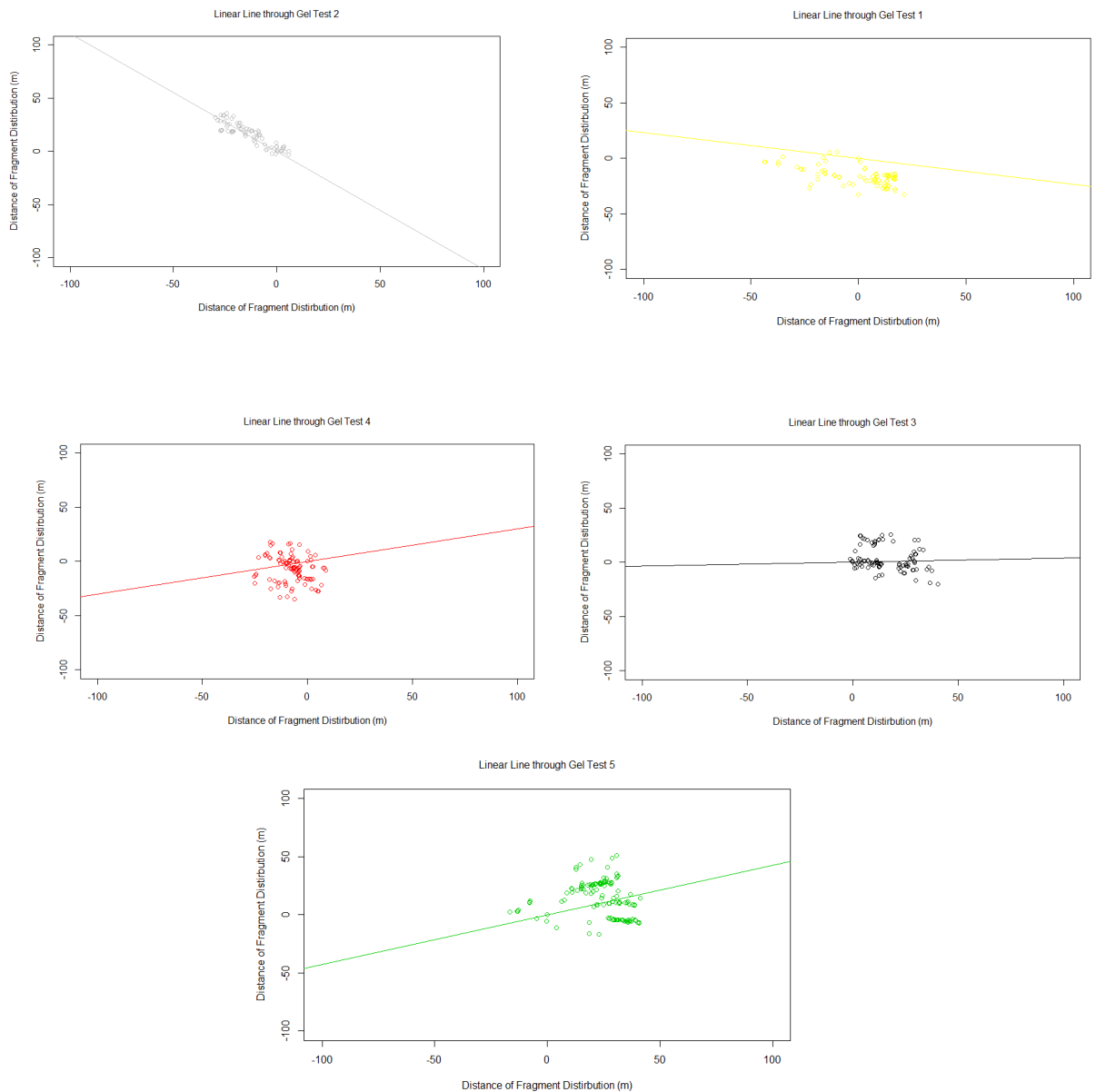
**Figure 7.1.** A photo comparison of the size of the both the piglets and the gel blocks that were used for this portion of the experiment.



**Figure 7.2.** A map detailing the location of the five gelatine blocks that were used in this section of the experiment (not to scale). The location of the piglets is also included and represented by the red squares.

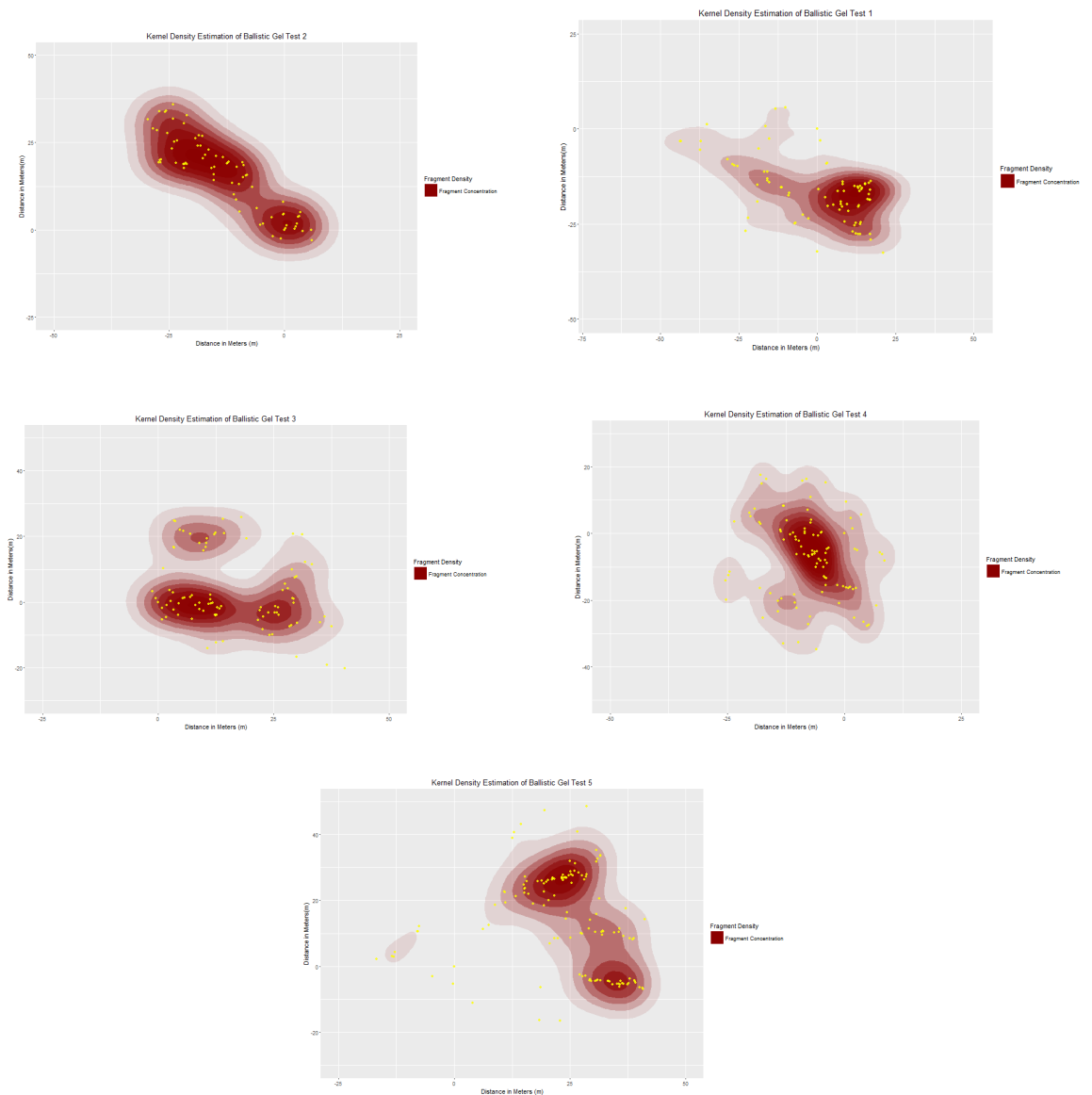
### 7.3 Gelatine Block Results

The data from the gelatine block section of the experiment was processed in the same way as the piglet target data. First a best-fit line was produced to tie the fragment points to their unique spatial location (see Figure 7.3). Once again this was employed as a means of tying the fragment points to their respective spatial location. As it can be observed in the below figures, the overall spatial data tends to cluster along the best fit line and move away from the blast centre (0,0).



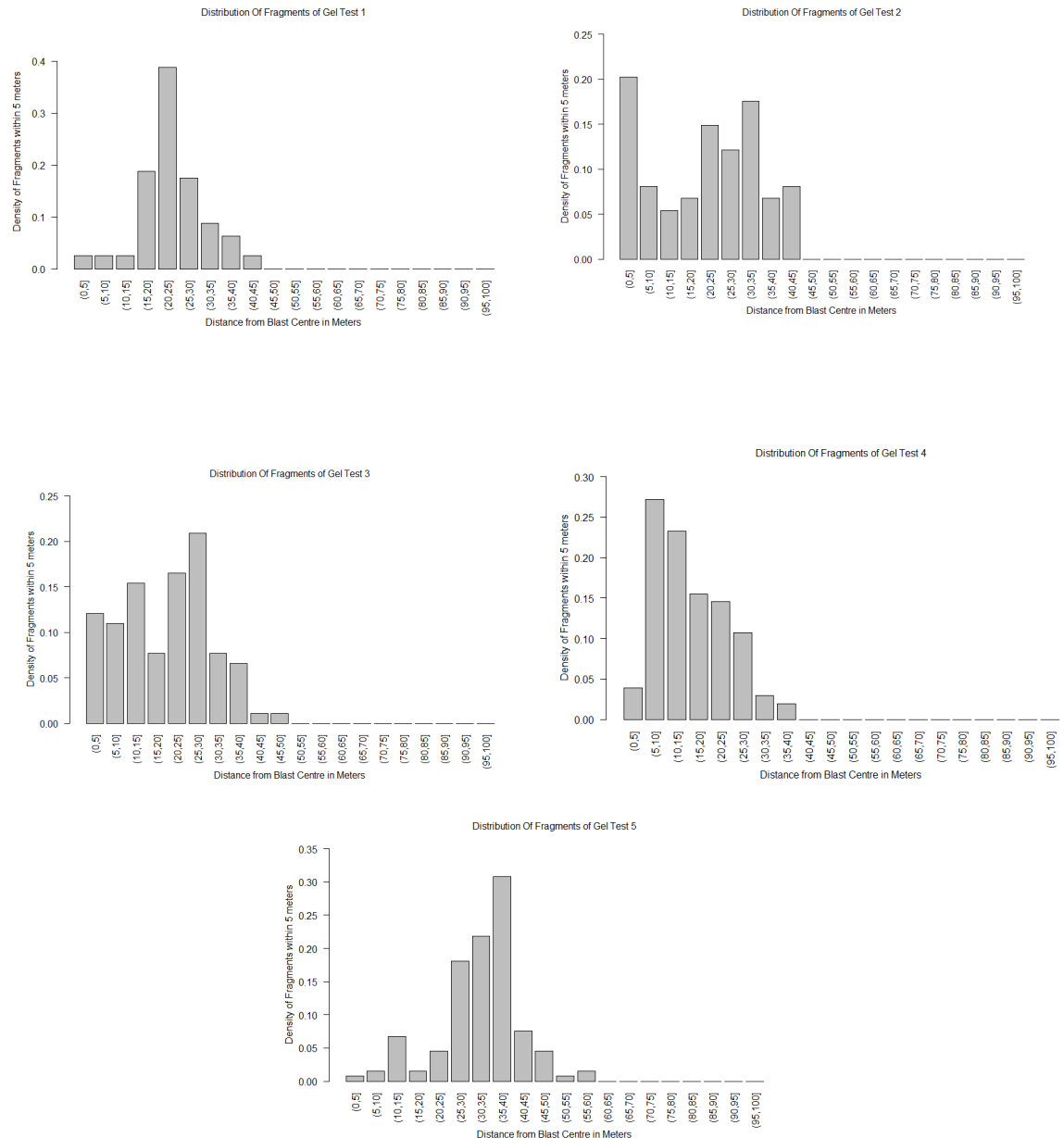
**Figure 7.3.** The best-fit line plots of gelatine block data.

Then the data was processed using a KDE (see Figure 7.4), which demonstrates the clustering of the fragment points or the ‘hot spots’. As the plots below demonstrate, the majority of the fragments landed near/at the blast centre and can be identified by the yellow colour on the red back ground. In the case of tests 1, 3 and 5 there are two separate areas of high fragmentation clustering. This may have been caused by the placement of the explosive device (which the researcher was not present for as noted earlier in the beginning of Chapter Five) being different and resulted in the fragmentation clustering in a different pattern.



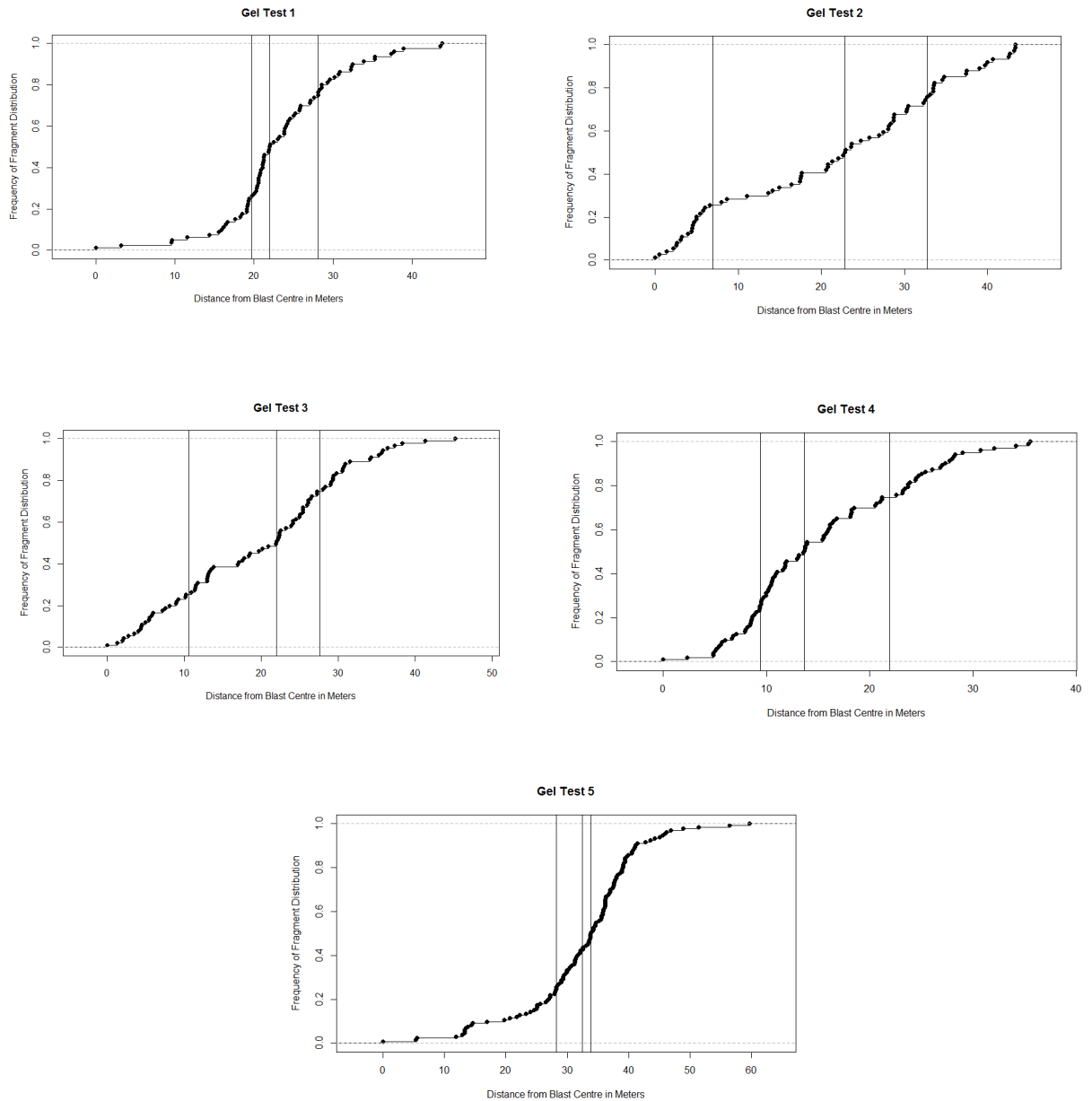
**Figure 7.4.** The KDE plots of the gelatine blocks

A density bar graph (see Figure 7.5) was produced next in the statistically analysis process. The fragments clustered around and at the centre of the blast, with a tendency to increase around 20- 25 meters from the blast centre before decreasing.



**Figure 7.5.** The density bar charts from the gelatine block data sets.

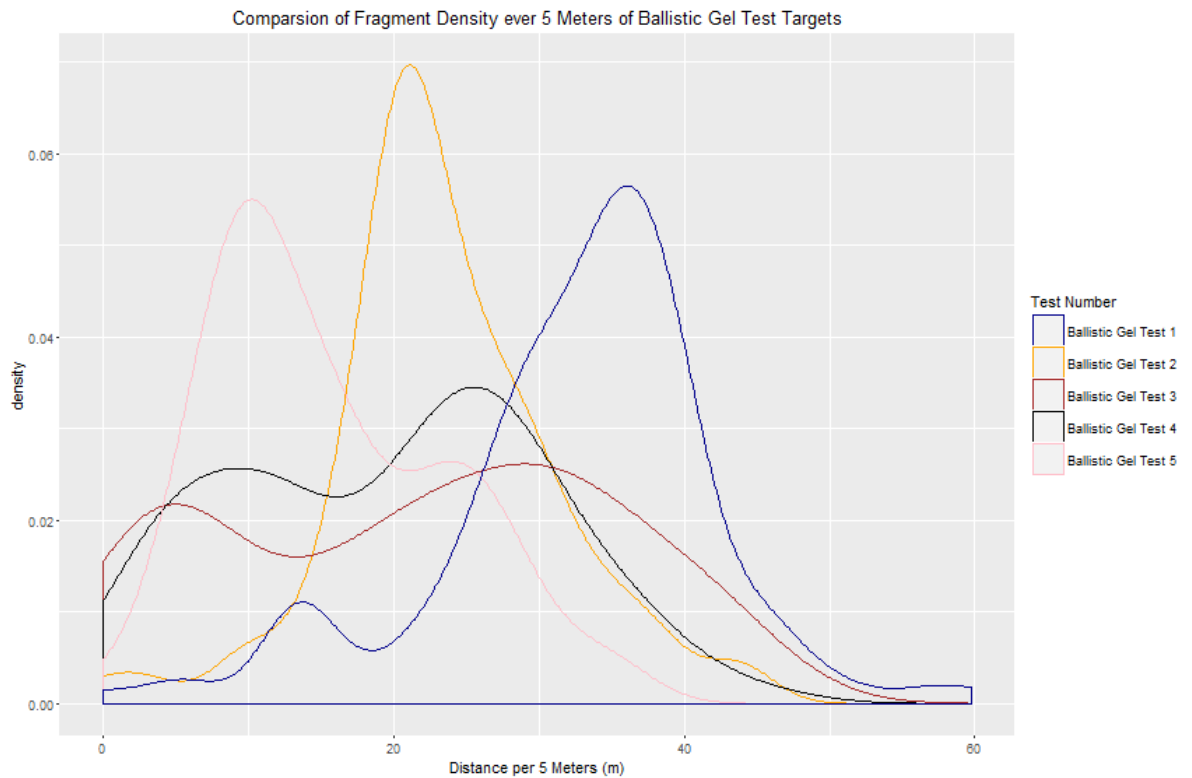
In the next stage, the cumulative density (see Figure 7.6) was calculated to identify the spatial patterning of the fragmentation. Vertical lines were inserted to represent the percentages of the fragments within the Q1, Median and Q3 respectively. In most cases, 50 percent of the total fragmentation density was observed within the first 30 meters



**Figure 7.6.** The cumulative density graphs of the gelatine block data set

The cumulative density of the individual five tests were then compared to one another (see Figure 7.7). In all the tests, there was a significant peak in fragment density observed before a decrease occurred. This was not uniform across the five tests, with only test 3 and 4 being slightly similar in nature. This may have been caused by the location of the gelatine blocks on the quarry site in relation to the rock piles that surround the area. Although all attempts were made to remove this as an impact factor, the blast wave in

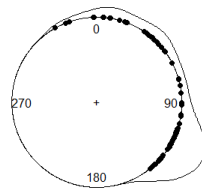
these instances may have hit the rock pile and refracted back into the area, increasing the overall direction of the fragmentation.



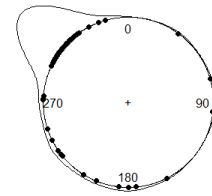
**Figure 7.7.** All of the gelatine test density distributions compared to one another.

Lastly, circular statistics (see Figure 7.8) were produced and illustrated visually the resulting directionality of the fragment spread. The degree at which the majority of the fragments are located can be directly traced back to the location and position of the explosive device.

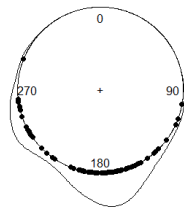
Circular Density of Fragment Distribution of Gel Test 1



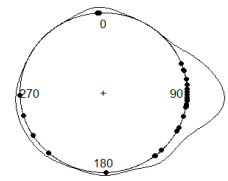
Circular Density of Fragment Distribution of Gel Test 2



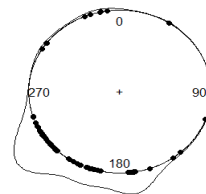
Circular Density of Fragment Distribution of Gel Test 3



Circular Density of Fragment Distribution of Gel Test 4



Circular Density of Fragment Distribution of Gel Test 5



**Figure 7.8.** The circular graphs of the gelatine blocks data set

Rayleigh's test of uniformity (see Table 7.1) was conducted in the next stage of the R studio program. The results demonstrate that the spread was heavily impacted by the placement of the bomb on the target and therefore the data is directional in nature. The p- value of  $p < 0.01$  indicates a rejection of the hypothesis that the spatial data fell equally around the blast centre.



Test Type and Number	Rayleigh's Test of Uniformity Result	P-Value
Gel Test 2	0.7567	p<0.01
Gel Test 3	0.7791	p<0.01
Gel Test 4	0.6054	p<0.01
Gel Test 5	0.771	p<0.01

**Table 7.1.** Rayleigh's test of uniformity conducted on the data set collected from the gelatine block section of the experiment.

Lastly, the Watson-Wheeler test was conducted to compare the spatial distributions statistically (see Table 7.2). These results illustrate the high impact that that precise placement of the explosive devices has on the resulting spatial distribution of the fragment given that all of the results from this test produced results with a p value < .05.

Test Number	Gel Test 1	Gel Test 2	Gel Test 3	Gel Test 4	Gel Test 5
Gel Test 1		109.5	119.7	5.31	146.8
Gel Test 2	109.5		89.18	50.42	97.24
Gel Test 3	119.7	89.18		42.76	24.72
Gel Test 4	5.31	50.42	42.76		46.04
Gel Test 5	146.8	97.24	24.72	46.04	

p-value<.05

**Table 7.2.** The Watson-Wheeler test results from the gelatine block data set.

One of the major differences observed between all of the five tests is that there is no commonality as to the distance where this increase in fragment density occurs. Another observation was that in several instances there were multiple areas of high fragmentation clustering. Although all steps were taken to ensure that each of the five tests were set up in the exact same manner, the researcher was not present when the explosive was set onto the target due to safety regulations on the range as previously noted. This may have meant that several of the targets were not set up exactly as outlined by the explosive engineers. It could also mean that the gelatine material is not a good tissue substitute for this type of forensic work as it does not produce consistent results

across test where the variables are kept constant. This would imply that scaled gelatine is not a workable model and other materials would need to be explored. It should be noted that only five tests were conducted and that more testing would be need to occur in order to come to a conclusion. The location of the experiments was a factor that the researchers had no control over and all steps were taken to prevent the overall location of the quarry walls from having any impact on the resulting spread (the blast wave refracting off of the walls back into the target tissue, creating further spread). None of the tests conducted produced a p-value greater then .05, therefore there is no similarities between the angles of highest fragmentation density present across all of the gelatine block tests. Following this was the series of tests described in Chapter Four that allowed closer statistical comparison of the small piglet and small gelatine sub-groups of data which is reported in section 7.4.

#### **7.4 Comparing the experimental results between the piglets and the gelatine blocks**

The main aim of the experimental work described here was to see if gelatine could be used as an alternative to biological tissue. This was done to address the difficulties that are often associated with trying to obtain biological tissue in the attempt to open up this field of research. The more experiments that are conducted, the larger the evidence-base that can be applied by practitioners both in the field and in the laboratory. In this section, results summarising the entire sub-group of piglet experiments and the entire sub-group of gel experiments are compared and contrasted.

Using the R program developed and data collected during the pilot experiments (DuBois *et al.* 2017 and Appendix A) and discussed in detail in Chapter Four, several conclusions can be made concerning the similarity between the piglet and gelatine data sets. One of these similarities is the impact of the weather on the resulting spatial distribution. In contrast with the experiments that were conducted earlier (see DuBois *et al.* 2017 and Appendix A, which was wet, rainy and windy), the tests in this section were conducted in weather that was hot, humid and with very little wind. In addition, these tests were conducted in an old quarry site, an area that was very sheltered from the wind in comparison to the wide open field that was employed in the tests conducted in the development of the R program (DuBois *et al.* 2017 Appendix A). This difference in environmental conditions can be observed in the maximum distance obtained by the

fragmentation of both the piglets and the gelatine. There are no large outliers in the maximum distance observed in either the piglet or gelatine (as observed in figures 5.6, 5.7, 5.8, 7.5, 7.6 and 7.7 respectively). The maximum distances all fall within a similar range, usually no more than 60 meters. Since the wind was never a large factor, this meant that the only variable that would be impacting the maximum fragment distance is the blast wave created by the explosive reaction. The impact that weather can have on the maximum distance is noted in how it impacts the chemical particles and how they are distributed (Abdul-Karim *et al.* 2016). The overall impact of the weather, although not a significant issue in this set of experiments, is an important factor that will need to be accounted for in any real world forensic investigation by practitioners and scientists.

The placement of the explosive device is another variable that impacts both the piglet and the gelatine targets similarly. As observed in Figures 5.9 and 7.8, along with tables 5.1, 5.2, 7.1 and 7.2, the angle at which the majority of the fragmentation falls around the blast centre is directly tied to the placement of the explosive device on the target tissue. Although the material in the two tests composed of different materials, the placement of the device on the target still impacted the overall spread. In Figures 5.9 and 7.8 which show the circular statistics from both the piglet (Figure 5.9) and gelatine blocks (Figure 7.8), the highest concentration of fragmentation fell within a certain angle range which was directly tied to the placement of the explosive device on the target. In Tables 5.1 and 7.1, the results of the Rayleigh's Test of Uniformity firmly rejected the hypothesis that the fragmentation fell evenly around the blast centre. Similarly, the results of the Watson-Wheeler test (Table 5.2 and 7.2) further supports this by demonstrating show dissimilar direction of blast angles The directional results can be understood in part because in all cases the explosive device was placed directly on the front of the target. This was to simulate a situation in which a single individual biological agent would explode with the bomb strapped to their front. This directional impact is a common thread across both the piglets and the gelatine blocks. However, it is acknowledged that the results above do not show particular consistency in terms of the actual vector direction of the blasts. One factor that could have contributed to the range of angle variation was that the explosive was placed without the researcher present, due to health and safety guidelines, although the same placement throughout was requested. This adds to the evidence that the range in the angles of the directionality is mainly due to the precise placement of the explosive device on the tissue target prior to the explosion taking place.

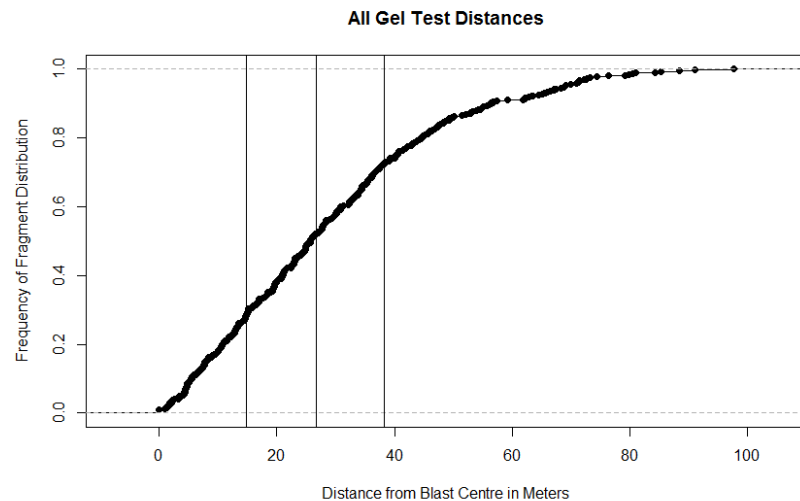
The distributions (of both piglet and gelatine fragments) appear to be highly sensitive to small variations in this sense.

The resulting spatial distributions can also all be described as one that cluster around the blast centre and decrease in frequency of fragments as the distance from the blast centre increases. The clusters can be observed in the density bar graph (Figure 5.6 and 7.5) which demonstrates this pattern and is present in both the piglet and gelatine data. In both the piglet and gelatine experiments the majority of the fragmentation falls within 30 meters, demonstrating a fairly high degree of comparability on this aspect. These clustering patterns can also be observed in the KDE plots in Figures 5.5 and 7.4 and further demonstrate that the majority of the fragmentation falls in and around the blast centre.

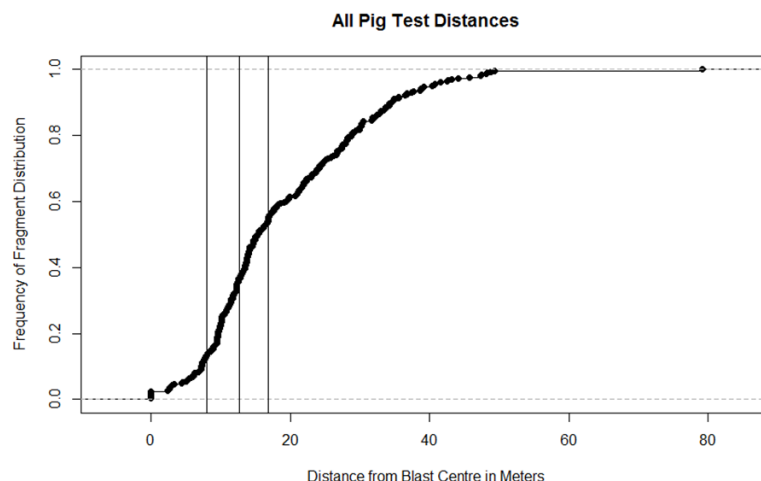
This common distributional pattern can be attributed to two factors. One, which is discussed in greater depth in section 2.4, is that the force of the blast wave that is produced by the chemical reaction that cause the explosion dissipates fairly quickly after the explosion. This means that the forces which initially created the fragmentation and cause it to move away from its original position on the target, is one that does not have the staying power to move the fragments very far. The second factor relates to the vacuum that is created after the blast wave moves through the environment. This creates an increase in the environmental pressure as it move out from the blast centre. When it moves away, the surrounding environmental pressure drops below its normal stable level in an attempt to stabilize and in doing so, creates a vacuum. This mean that any debris that is created by the blast wave can then be sucked back towards the blast centre. The vacuum, therefore, limits the overall distance that the fragmentation can travel and aids in producing the observed clustering.

In just examining the maximum distance that the fragments travelled, the piglet and the gelatine experiments were fairly similar to each other. Figures 7.9 and 7.10 show the overall fragment density distribution for the scaled gels and the piglets respectively. By comparing these figures, although there is an outlier in Piglet Test 1 of 80 meters, it can be observed that for the remaining tests the maximum distance falls around 60 meters. In terms of the shapes of the distributions, as observed in Figure 7.9, the majority of the gelatine fragments had the tendency to fall closer to the 20 to 30 meter mark. The piglet fragments, shown in Figure 7.10 on the other hand had the tendency to fall closer to

the 15 to 20 meter mark (Figure 7.10). Although there are cases where gelatine fragment density fell within a similar range as the majority of the piglet tissue and vice versa, the main trend is still that gelatine fragments distribute at slightly greater distance than the piglet fragments (Figure 7.9). Overall, the gelatine fragments travel further than the scaled pig fragments.



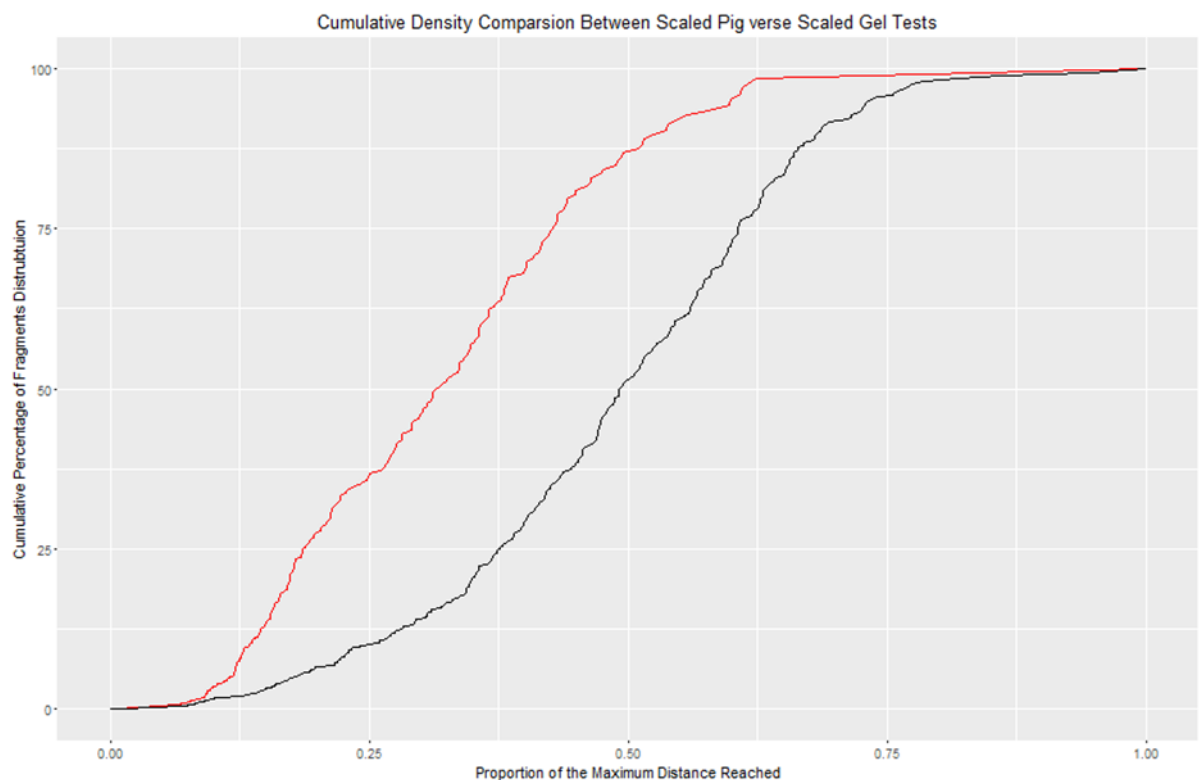
**Figure 7.9.** The combined cumulative density data of all the gelatine fragments. 50 % of the fragments on average were located between 20 to 30 meters away from the blast centre.



**Figure 7.10.** The combined cumulative density data of the entire piglet fragments. 50% of the fragments on average were located between 15 to 20 meters away from the blast centre.

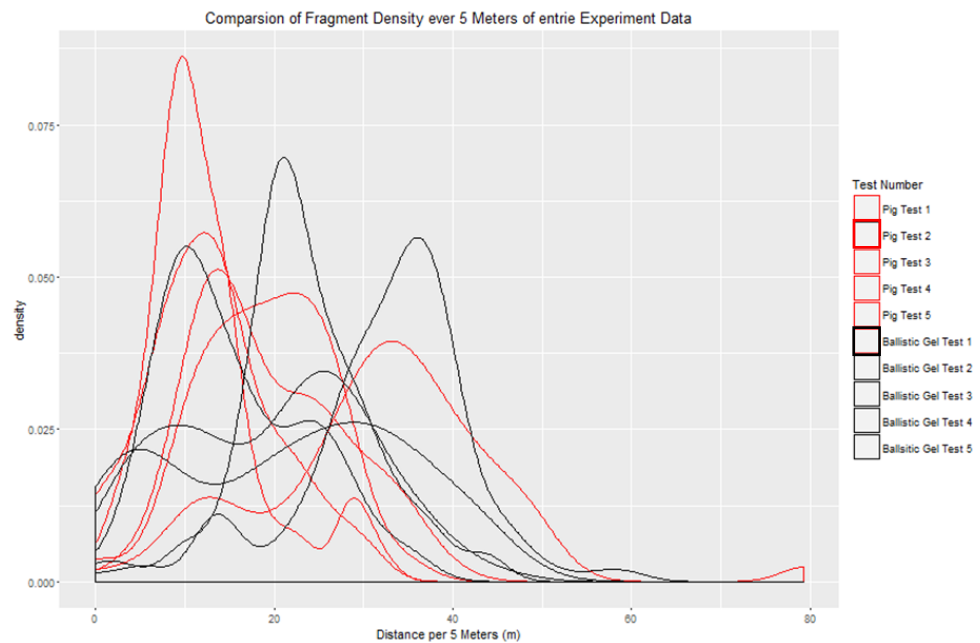
A two-sample Kolmogorov-Smirnov test or ks-test was used to explore how similar the distribution from piglet experiments and the scaled gelatine experiments were

to each other. The resulting p-value was  $9.703\text{e-}11$  which indicates that the two data sets come from different samples. This is further highlighted in the combined cumulative density graph (see Figure 7.11). Once again, to achieve this comparison the proportion of the maximum distance reached was used as a way to directly compare the shape of the distribution of each experiment to each other. Although the fragment density is slightly similar in the distance right at the blast centre for both tests, the vast majority of the two experiments are vastly different from each other.



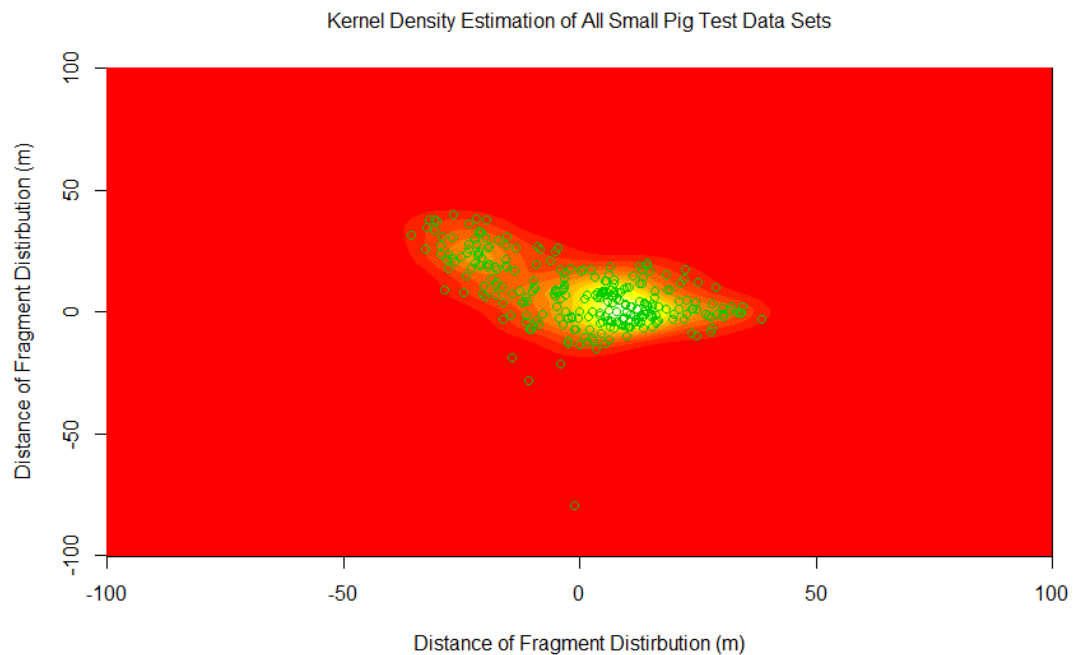
**Figure 7.11.** The cumulative density comparison graph comparing the data from the scaled pig experiments (represented in red) to the data from the scaled gel experiments.

This difference between the piglet and scaled gelatine targets is demonstrated further in the comparison of fragment density across 5 meters (see Figure 7.12). The average gelatine fragment density occurs at a further distance from the blast centre when compared as a whole to the piglet fragment density.

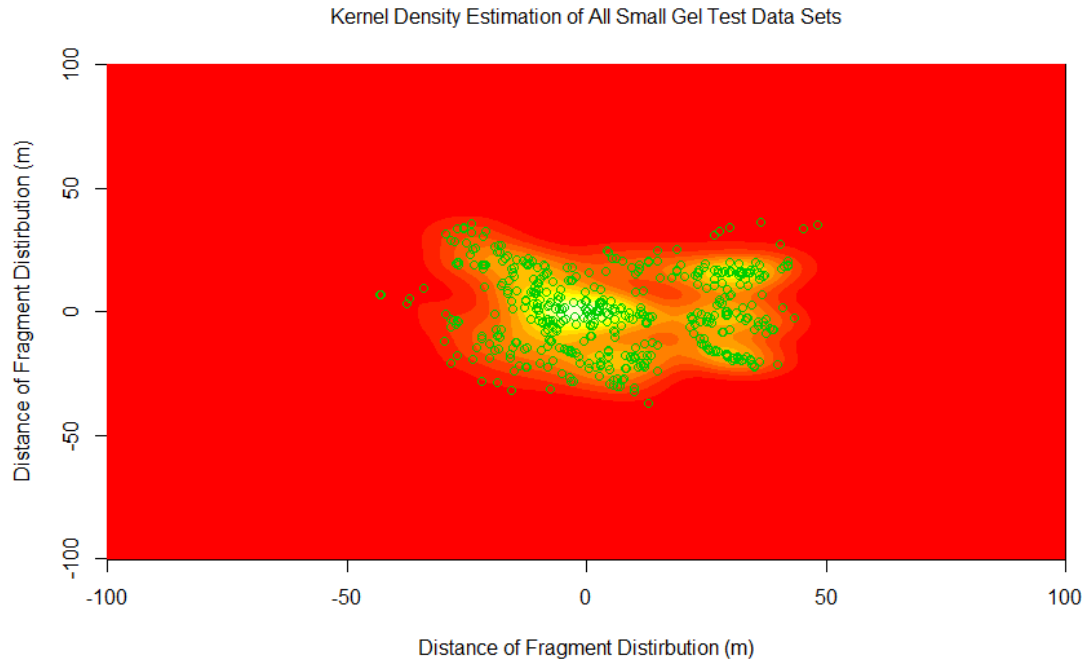


**Figure 7.12.** The comparison of both the piglet density distribution and the gelatine density distribution.

Another statistical test that was conduct was a kernel density estimation (KDE) which can be observed below in Figure 7.13 for the piglet targets and in Figure 7.14 for the scaled gelatine target. In the case of both sets of data, the majority of the fragmentation created in the blast landed at/or near the blast centre. As the distance from the blast centre increased, the resulting fragmentation distribution decreased.



**Figure 7.13.** The KDE of the piglet test which show the distribution of the fragmentation spread.



**Figure 7.14.** The KDE of the scaled gelatine test which shows the distribution of the fragmentation spread.

The main reason for this difference between the two target tissue distributions appears to be the difference in the material make-up of each target. The gelatine (see section 2.5.2 and section 6.4 for more details) was initially designed to act in a similar manner to how biological tissue would act when exposed to impact forces. Impact force is vastly different from the force that is produced during an explosion. With the similarities observed in the course of this research, gelatine may not be a suitable as a tissue replacement for all situational forces. These differences may also be attributed to the difference that gelatine has on a microscopic level to biological tissue. This may have caused the gelatine fragments to be effected in a different manner to the heat created by the explosions, thus, creating the difference observed in the fragmentation distribution between the two sets of data. This difference that the material composition may play in the overall fragmentation distribution was noted in the results following the large gelatine experiment. This lack of consistency between the target materials would make sense when compared on the scaled level. A final reason for this difference in fragment distribution between the two experiments is in how the scaled pig targets were stored. As discussed in Chapter Five in which the data sets of the large pig experiments are compared to the scaled pig data, the scaled pigs were stored in a freezer. Although all attempts were made to fully thaw the targets, because of the extreme heat the day of the



tests it was decided to explode the scaled pigs before the gel blocks. This was done to prevent any heat decomposition of the piglets. Any remaining frozen flesh may have influenced the way in which the scaled pig tissue fragmented, resulting in the fragments landing closer to the blast centre when compared to the scaled gel data.

## **7.5 Conclusion**

One of the major conclusions from the comparison of these two data sets to each other is that there are significant differences between the piglet targets and the gelatine targets. Although the methodology that was employed in both instances was the same, the overall distribution density and fragment distribution differed enough to be statistically significant. Even though the overall spread pattern was similar in that in each case the fragmentation landed at or near the blast centre, there is still enough difference to highlight that at the scaled level the piglet target and the gelatine target differed from each other. This may indicate that at a scaled level a tissue substitute would not work for this type of forensic experiments. These ideas will be explored in greater detail in Chapter Nine.

## **Chapter Eight. Thoughts and Comments from Practitioners present at the Training Exercise**

### **8.1 Introduction**

One of the objectives of this research, as set out in section 3.3, is to assess how realistic experimental results, such as those described in Chapters Five, Six and Seven, are to real world situations. Whilst it is not realistic to expect access to forensic evidence from the site of an actual lone-bomber explosion, it is possible to gain understanding by examining training exercises, which are designed to give a real world context to involved practitioners. During the course of this research, the researcher was invited to participate in an advance post blast training exercise that was primarily run by the Montgomery County Sheriff's Office Bomb Disposal Team. Although the researcher was invited to participate, she was not included in the design process of the training exercise. This included the bomb design, explosive composite, etc. Ethical approval was obtained by the police office to employ the use of the deer. First responders from the local and state police, fire departments, ambulance services and the emergency management team from the surrounding tri-state area (Pennsylvania, New Jersey, and New York) took part in this three day event. In addition to the Sheriff's Office bomb technicians, members of the Philadelphia Federal Bureau of Investigation, the Philadelphia Department of Justice Bureau of Alcohol, Tobacco, Firearms and Explosives, Philadelphia Secret Service Office and other Pennsylvanian based Bomb Disposal Units were on site to help run and take part in the training exercise. It should be noted that no forensic department or forensic member associated with the various departments were on site. This was a training exercise designed from a law enforcement perspective and to address the role of law enforcement on this type of scene. This training exercise never the less created a good opportunity to observe an explosion in a more realistic forensic setting and a comparison to what was undertaken during the PhD experiments.

The three day exercise was set up as follows. The first day was spent conducting the trial explosions, with the second day spent conducting a search and recovery process in the debris field. On the third day, participants presented findings concerning the search and recovery of the resulting blast area. In this chapter, the set- up of the explosion and

the general debris field observed are compared to the overall findings from the research conducted as a part of this PhD. One major disappointment that occurred during this training exercise was that no spatial data was collected of the debris field by the participants. Although the researcher attempted to provide a total station to collect this type of data, the exercise was more of a law enforcement training exercise than a forensic data collection exercise. It should be noted that there was no fragmentation of the targets which restricted the collection of spatial data. Whether this is more realistic to this particular type of situation (lone bomber with explosives attached/directly in contact with body) will be explored later on in the following Chapter Nine within section 9.1.1. It is noted that any comparison between the training exercise and the PhD findings in the chapter will be general in nature. One theme of this section of the research was to investigate the degree to which the experiments can represent real world situations. The second half of this chapter extends the analysis of the bus experiment by reporting responses to a set of questions that were asked of the various law enforcement agencies relating to how forensics evidence bases play a role in how they would conduct a real world post-blast investigation.

## **8.2 Bus experimental set –up and execution**

The training exercise was conducted on the grounds of the Graterford Correctional Facility Pennsylvania. At 7:30 am on the first day, the SEPTA bus (which had been donated by the city of Philadelphia and was already present on site) was inspected and cleared of any extra debris. One of two large gelatine blocks provided for the experiment by the researcher was loaded onto the bus and placed in the centre of the back row (see Figures 8.1, 8.2, 8.3, 8.4 and 8.9 for more details). A crate was placed below which would hold a purse containing the explosive device, simulating a device that would have been held in the lap of the individual (see Figure 8.9 for more details). For this blast, 1.6 kgs of smokeless powder and bb pellets (small circle metal balls) were placed into a pressure cooker to create the blast and a cell phone was employed as the means of triggering the device (see Figures 8.5, 8.6, 8.7, 8.8 for more detail). A deer cadaver was positioned two rows up from the back row where the gelatine block was placed to add a bystander victim and to also observe how this type of explosive material impacted biological tissue (see Figure 8.10). Sunglasses, a used cigarette and an empty cigarette carton were placed on

the deer to add additional contextual forensic evidence that was hoped would be located and collected by those involved in the training exercise.



**Figure 8.1.** A photograph of the side of the SEPTA bus prior to the explosives training exercise.



**Figure 8.2.** A picture of the back of the same SEPTA prior to the explosive training exercise



**Figure 8.3.** A photograph of the other side of the SEPTS bus prior to the explosive training exercise.





**Figure 8.4.** A photograph of the inside of the bus prior to the explosive training exercise. The back row of the bus is where one of the gelatine blocks was placed.



**Figure 8.5.** The pressure cooker bomb in the back pack prior to being placed inside the bus.

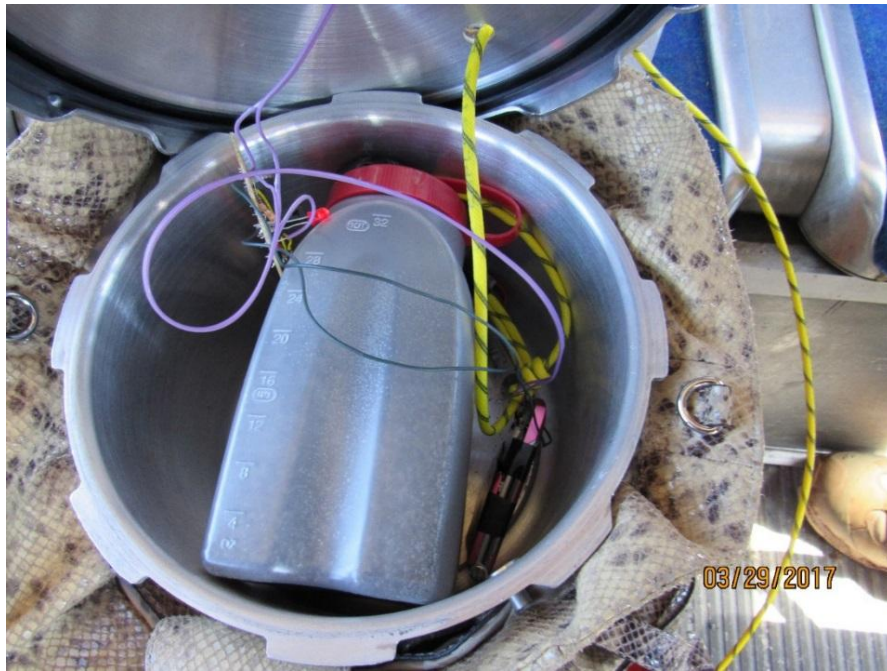


**Figure 8.6.** The pressure cooker bomb prior to placement in the bus.

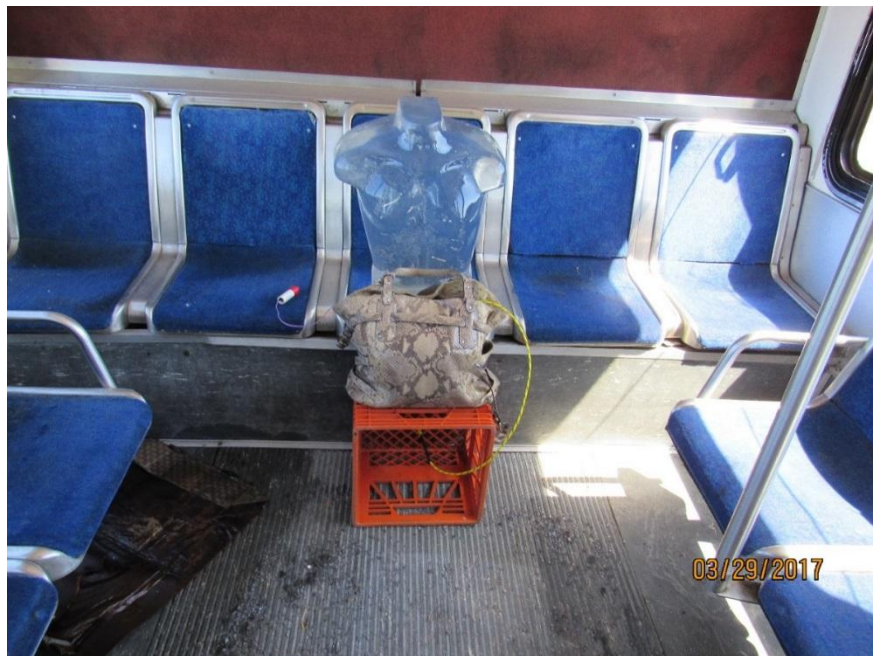


**Figure 8.7.** Inside the pressure cooker bomb prior without the explosive material, a cell phone (here, sitting on the base of the cooker) was used to trigger the device





**Figure 8.8.** The pressure cooker bomb with the explosive material smokeless powder- bb pellets was placed inside the explosive material to increase the damage created by the explosion.



**Figure 8.9.** The gelatine block placed in the centre back row of the bus. The pressure cooker bomb, which is located in the back pack, was placed on top of a plastic crate to simulate the bomber having the device on their lap.



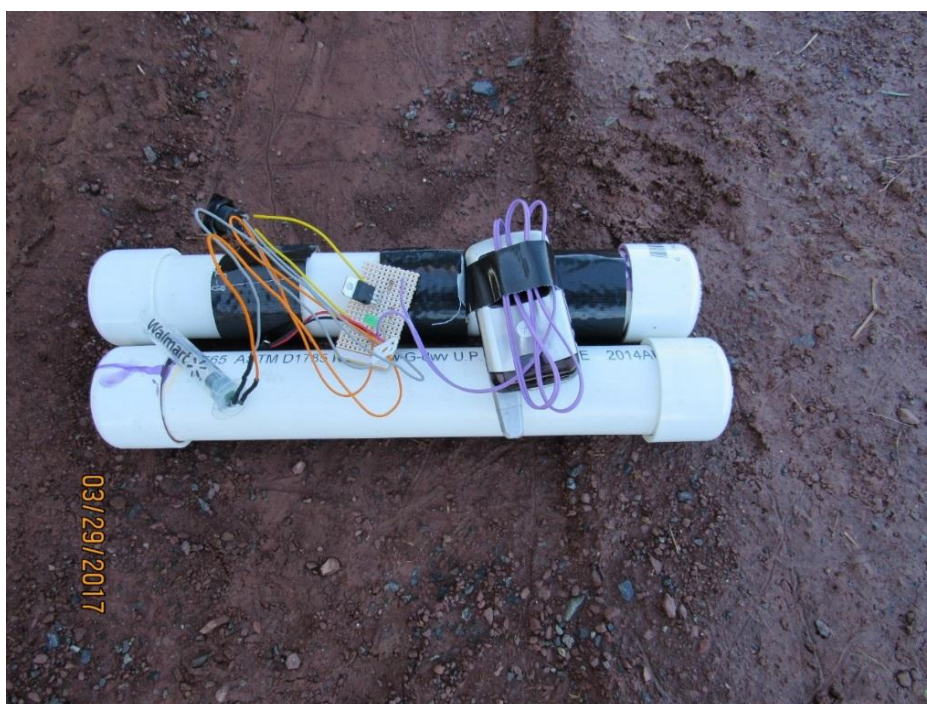


**Figure 8.10.** The deer which represented a bystander and was used to observe how the explosion would affect biological tissue. Several pieces of forensic evidence (sunglasses, cigarette, and cigarette package) were placed on the deer to see if they could be collected later on by the students in the advance post-blast course.

At 1.00 pm the bus was blown up, with video taken from a police helicopter and remote video cameras (see Figure 8.11 for the bus post first blast). A second blast, external to the bus, was conducted at 1:30 pm. This involved the second large gelatine block that was placed 6.1 meters behind the bus. The second device consisted of two pipe bombs containing 0.7 kgs of smokeless powder and bb pellets with a cell phone employed to trigger the device (see Figures 8.12, 8.13, 8.14 for more details). The second blast was designed to replicate an attack on first responders in a scenario where they initially arrive on site and are then attacked by a secondary attacker.



**Figure 8.11.** The bus following the explosions of the back pack bomb inside of the bus



**Figure 8.12.** The second explosive device, which was a pipe bomb filed with smokeless powder and bb pellets. Once again a cell phone was used to trigger the device.





**Figure 8.13.** The second gelatine block which was placed 20 feet away from the back of the bus. The pipe bomb was placed in a small bag and placed directly in front of the gel block.



**Figure 8.14.** The bus prior to the secondary explosion – the gelatine block can be observed in the back (in red circle).

Once both explosions had occurred, the resulting debris field was searched and declared safe (see Figure 8.15 for debris field example). The debris field comprised of a range of materials that once made up the bus. These materials ranged from glass, plastic and fabric.



**Figure 8.15.** A photograph of the debris field after both of the explosions.

The inside of the bus was also examined after the blasts had occurred to observe what type of damage had been created (see Figure 8.16 and 8.17). One aspect to note was the extensive damage created by the bb-pellets on both of the targets on the bus (see Figure 8.18, 8.19, 8.20). The site of the blast on the bus was also identified in the course of this process (see Figure 8.20).





**Figure 8.16.** The inside of the bus after the two explosions had taken place.



**Figure 8.17.** Inside of the bus, the back row where the bomb and the gel block were placed.



**Figure 8.18.** Inside the bus, a view looking at the bus ceiling showing the escape hatch has been blown off and the ceiling is full of holes created by the bb-pellets (several are indicated by the red arrows).



**Figure 8.19.** A close-up of the back row of the bus following the explosions, the holes from the bb-pellets can be observed.





**Figure 8.20.** A close-up of the blast centre where the bomb and the gelatine block were placed prior to the explosion occurring.

The gelatine block and the deer were both identified during the search of the bus (see Figure 8.21 and 8.22 respectively). It should be noted that in both instances, neither target was fragmented but were full of bb-pellets and had thermal burns. In the case of the deer, the forensic evidence that was placed on it was no longer located on the body, but was located on/near the deer.



**Figure 8.21.** The gelatine block following the explosion. No fragmentation occurred, but the block was charred and full of fragmentation (bb-pellets, metal fragments, etc.)



**Figure 8.22.** The deer following the explosion. There was no fragmentation, but the deer was full of fragmentation (bb-pellets, metal, etc.).



As the search of the debris field continued, the second gelatine block was located around 20 meters from its original position. It landed on its front in a ditch by the bus (see Figure 8.23) and was not fragmented in any way but was full of bb-pellets (see Figure 8.24).



**Figure 8.23.** The second gelatine block.



**Figure 8.24.** The second gelatine block rotated on to its back.

The site was preserved for the next day in which those involved in the training exercise would conduct a search of the site (see Figure 8.25 for more details).



**Figure 8.25.** The side of the bus post explosions with the police helicopter in the background that was on scene to take photographs and video from the air.

On the second day of the training exercise the site was doubled checked to make sure it had not been disturbed during the evening. The larger training exercise class arrived on the scene around 8 am and was separated into four separate groups of between 8 to 10 individuals with similar backgrounds in both work experiences and job descriptions (e.g., police, fire fighters, paramedics, etc were all placed within groups together). Each of the groups was then assigned a section of the overall site to conduct a search and recovery process. The first group was assigned to search the inside of the bus, the second and third were placed on either side of the bus, while the fourth group was assigned to search the site of the secondary explosion. As each group searched their assigned locations following the Waldron springs protocol (outlined in section 2.3.1), members of the different agencies involved in running the training exercise walked around to help answer any questions that those groups may have had. The evidence was unfortunately not recorded in-situ due to no total station being present and the need to only be on site for a specific period of time. Once all of the groups had finished conducting the search and recovery of their assigned areas the site was cleaned of all the remaining debris and the field portion of the training exercise was complete.

### **8.3 Response from Practitioners taken during the Bus Training Exercise**

During the course of the second day of the bus training exercise, the practitioners who were on site to assist and provide guidance for the students were asked a series of questions (by this researcher) pertaining to their views on forensic science and the role it plays in a criminal investigation of an explosive event in the field. The questions posed to the practitioners were qualitative in nature. Qualitative research is applied heavily within the field of social science and generally focus on asking question about the 'how' and the 'why' (Savin-Baden and Major 2013; Alasuutari 2010). One of the most applied qualitative methods is to interview participants, which is employed here in this section of the PhD (Savin-Baden and Major 2013; Alasuutari 2010). This method aims to ask the participants their views on a particular area or subject, providing a unique perspective on the studied areas and can highlight areas of study that a researcher may not have thought of before (Savin-Baden and Major 2013). One major drawback in applying this type of research is the issue of trustworthiness or if a response provided by the participant is an accurate representation of what actually occurs (Savin-Baden and Major 2013). Another

drawback is that the answer provided cannot be statistically measured as they are the viewpoints of a particular individual. Furthermore, since they are the views of a single individual, they can be influenced by that individual's personal biases and experiences (Savin-Baden and Major 2013; Alasuutari 2010). Nevertheless, if applied on a wide enough basis, qualitative research can provide a personal, in-depth look at specific research areas (Savin-Baden and Major 2013; Alasuutari 2010).

The individuals who were interviewed during this experiment were law enforcement personnel and not forensic scientists. The questions listed below were designed to gain an insight into how law enforcement personnel view forensic science given that they tend to have a different focus in the overall hierarchy of propositions (as outlined in Cook *et al.* 1998 and further described in section 2.1.1) towards a quick apprehension of those involved in the crime and not necessarily on the overall evidence collection, analysis and interpretation that a forensic scientist tends to focus on. This difference in focus can lead to ineffective communication and feedback between law enforcement and forensic scientists (Mnookin 2011; Ludwig and Fraser 2014). Therefore, it is important to gain an understanding of the current views held by law enforcement towards forensic science and its applications to a criminal investigation. This provides the opportunity to identify areas where communication concerning not only the criminal investigation in the field but also in the development of forensic experimentation between these two groups can be improved. This is to ensure that the science used to address an issue within a criminal investigation is not only relevant, but also accurate (NAS 2009, Government Chief Scientific Advisor (GCSA) 2015; Edward 2009; Risinger 2009; Tully 2015; Saks and Koehler 2005; Cole 2006; Bowers 2006; Christensen and Crowder 2009) and beneficial in a court of law.

It should also be noted that notification of being able to even ask such questions came the week before the researcher left to head to the U.S. to conduct both the large gelatine experiment (see Chapter Six for more details) and participate in helping to run the bus training exercise. Since time was restricted seven key questions were prepared. The responses were recorded on site in an attempt to make the interview process as informal as possible. The relationships which allowed these questions to be asked were developed among these professionals over the course of the four years. Numerous times it was noted that members of the scientific and academic community were outsiders who did not understand this aspect of law enforcement and that the researcher was considered



to be an exception by the participants. Within this context it was determined that the best way to get the most accurate response was to do so in an informal manner. This meant that questions were not recorded using a tape recorder, but were instead hand-written by the researcher. Although the exact phrasing of the response was not recorded, a paraphrased response to each question was recorded to the researcher's best ability. No names or positions were recorded, only the organization which they belonged; this was done to provide anonymity to those who participated. Two members from each of the representing agencies (ATF, FBI, and the Sheriff's Office) were interviewed individually (6 participants in total). All had multiple years of experience within their respective fields as criminal investigators. The questions and the following response are discussed below.

### **8.3.1 In a real life situation, how applicable and useful are the forensic search and recovery protocols that are being taught today? What about in an active military zone?**

One of the first questions asked of the experts who were helping to run this training exercise focused on how applicable the type of forensic search and recovery training they were teaching was to other types of explosive scenes. The example given in this instance was that of an explosive event which has taken place in a war zone, since in this situation the site would not always be protected or safe from enemy fire. Members of the Department of Justice Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) responded by stating that this type of training exercise was 'extremely important' in that it helped to teach the systemic search and recovery process that would be implemented on a real life scene. The ATF officers went on to state that by teaching members of different first responder organizations what would be expected of them on a scene like this, it makes the process of conducting this type of forensic investigation in a real world situation much more efficient. Furthermore, the ATF officers went on to explain that on any explosive scene, the pressure to clear a scene is very intense. This is due to wanting to collect the evidence as soon as possible to start to figure out not only who conducted the explosion but also to try and restore a sense of normalcy for the public. Therefore, if everyone has an understanding of how to process a scene like this, the faster this goal can be achieved.

Two middle ranking members of the Sheriff's Office Bomb and Hazardous Device Disposal Unit responded in much the same manner by adding that when individuals respond to a scene which involves explosives, it makes the overall organization of the forensic recovery much more efficient if those individuals already know what role they needed to fill. The members of the of the Federal Bureau of Investigation (FBI) Technical Bomb Technicians responded differently, suggesting that although this type of training works in a civilian type situation, in instances in an active military zone it would not work. One of the FBI agents went on to state that in an active military setting, a special type of search needs to be conducted, called a sensitive site exploitation. This skill is taught at an advanced military training course. Individuals there are taught to recover only what you can find immediately and to leave the scene in as fast as possible manner. The agent went on to state that this is very different from how a forensic investigation is conducted on an explosion in a non-active military area. In this situation the traditional forensic process, which can be very time consuming to conduct properly, is often not an option.

In examining the responses from all of the investigators who took part in the questionnaire, several things of note can be identified. In the case of the officers from the ATF and the Sheriff's office, they were not wrong in stating that this training works in a civilian setting, as they are trained to investigate events that occur in a civilian setting. The ATF and Sheriff's office role in explosive investigations is focused solely on criminal explosives, while the FBI is charged with investigating terrorist bombing. The FBI members who were interviewed also currently serve as either reserve military EOD or as an FBI special advisor in active military areas. This would make their response different in that they have had to investigate different types of explosive scenes in different forensic contexts.

### **8.3.2 What types of questions are you asked when giving witness testimony in relation to serious explosive events?**

When questioned about what they are normally asked when providing expert witness testimony in a court case, the ATF members responded that they are often asked about what they saw when they first arrived on the site and what steps they employed to process the scene. A FBI team member said that it depends on the prosecution or the

defence and what their line of questioning is. Much like the response given by the ATF agents, the FBI agents stated that they are often asked about the techniques used to process the scene. The member of the Sheriff's office stated that they are often asked to describe their background, qualification training in addition to what they witnessed when they arrived on site and what techniques they employed to determine what type of explosives was utilized. Overall, the responses given by the individuals from all three agencies were very similar. When questioned in a legal setting, they are often asked what qualifies them as members of law enforcement for their opinion and what they saw/did on site are all important aspects.

### **8.3.3 When asked for your professional opinion on the likelihood of certain scenarios what do you use to make an assessment?**

In forming their opinions about what occurred on a scene, a Sheriff's office member stated that they rely heavily on their training and experience to form an opinion as to what occurred on a blast site. They look at the damage created, the bomb components located through a search of the site, and also considered some witness testimony. They stated that witness testimony is taken with caution as many people are in shock after such events and their ability to accurately recall the events prior to and after the explosion can be hindered. The ATF officers also stated that they rely on their experiences and years of training when drawing conclusions as to what occurred on a scene. They also stated that common sense plays a role in coming to their conclusions. Lastly, the FBI agents additionally suggested that they start with examining the post blast scene, to build a picture of what happened.

When examining the responses to this question, one of the main points was that for all the individuals their own experience and training played a huge role in determining what occurred. What they have seen before, what they have been taught to focus on, etc., all impact how these investigators determine what is important and what is not. None of the individuals interviewed talked about empirical studies or forensic experiments having an impact on how or what they may examine to achieve a determination of what occurred on a scene.

#### **8.3.4 Do you have a good professional relationship with forensic personal – in the sense that you can comment on what you think is working or needs to change?**

When asked about their relationship with forensic personal, the ATF agents stated that they have a very good working relationship with the forensic personal attached to their agency. The ATF agents further explained that while they are on an explosive investigation they will be on the phone with forensic personnel all day asking them what they should be recovering and where the agents should be focusing their attentions. This collaboration with forensic personnel also extends to the ATF national response team (the ATF members present were not a part of this team) that respond to major explosive events. This special team has integrated forensic personnel that will travel with the other ATF agents. The FBI members answered similarly and went further by stating that they are trained in basic forensic techniques to help agents better understand what needs to be collected on an explosive scene. The Sheriff's office responded differently stating that although they have a good relationship with the forensic personnel attached to their office, some did wish that they had more forensic training of their own from the police academy. Currently, when they go to a scene, they know what will be useful for them in terms of policing but not so much for what may be useful in a forensic context.

This difference noted above may be due to how much funding the different departments receive when they train recruits. Federal agencies have vast resources (Federal Bureau of Investigation 2017; Bureau of Alcohol, Tobacco, Firearms, and Explosive 2017), whereas local and state level law enforcement are often struggling to balance budgets due to the economic downturn that has hit many communities in the U.S. (United States Department of Justice Civil Rights Division 2015; Police Executive Research Forum 2010; Police Executive Research Forum 2013). This means that at a federal level, individuals are trained to deal with forensic scene in a more in-depth manner compared with those individuals who serve on a local or state level are.

#### **8.3.5 Do you think there is enough connectivity between the different players in any given forensic investigation? Why or why not?**

When asked this question, the ATF officers stated that it truly depends on the individuals working the scene. Given the right people and the right training things can run smoothly. They stressed that on an investigation like the training exercise where the



interviews occurred, the pressure to quickly complete an investigation is immense from senior command and this can often lead to power struggles between different departments for control. On the ground, the individuals just want to get the job done, but outside pressures can impact this. This sentiment was also expressed by member of the Sheriff's office and the FBI, who both added that post-blast training exercise such as the bus experiment do help to make things run more smoothly on a real scene. When people from different departments understand their role and the role of others, then the process as a whole runs more efficiently.

When examining the responses, one of the implications of this discussion is that training is a vital tool in making sure during a real world investigation that all the different agencies are able to work together. This type of training helps to teach people about the process holistically and what would be expected of them if this type of situation occurred in the real world. This training also helps to ease the inter-department rivalries as the different forces learn what other agencies can bring to the table and how those skill sets may work in complementary ways to their own. One drawback of the bus training exercise was that the forensic members of the various organisations were not present on site. This meant that although the views of law enforcement were explored, the perspective of the forensic members of these respective organizations were not. This meant that the true nature of the connectivity of all those involved in investigating a scene like the one that was present at the training exercise could not be fully examined.

#### **8.3.6 How frequently do you use evidence bases in your line of work (for example, scientific accounts of what might occur in explosions)?**

The answer to this question by all the individuals from across the different agencies was that they do not use any sort of evidence base in their line of work. What they do rely on is experience and training to form opinions about what may have occurred. Many of those investigating officers from all three agencies thought that the forensic personnel may employ evidence databases but as field officers they do not.

When examining the answers to this question, what was most evident was the degree to which training and experience are the default mechanisms used in the field by those who are the first to respond and investigate these types of forensic scenes. What they have been exposed to in the past, both in training and in the field will drive how they

will interpret a scene. Scientific studies and the findings associated with them did not play a particularly large role in how any one of the investigators who participated in the questionnaire will interpret the evidence located at a scene.

**8.3.7 What do you want to see either change/improve in the practice of undertaking forensic investigations? What areas within in the field of explosives in particular do you think need to be investigated further or better understood?**

Members of the ATF suggested that one aspect of this type of investigation that needs to be improved is the time it takes to fully investigate a scene correctly. With the pressure to complete an investigation coupled with the immense time needed to properly investigate a scene, it can lead to frustration among investigators on the scene. Both speed and accuracy are necessary and techniques that help to provide both would help in how these scenes are processed. The Sheriff's office member thought that the current methods worked sufficiently but more training exercises were needed in order to teach first responders how to correctly process a forensic scene. The FBI also expressed this sentiment, stating that since the Boston Marathon Bombing there has been a large push towards having first responders trained in post-blast investigations. One of the problems noted was that these types of exercises are costly to produce, so if there was a way to decrease cost associated with obtaining the materials to conduct this type of exercise that would aid in training more first responders.

Overall, the idea of more efficient search techniques coupled with cheaper training materials were widely cited by all the members of the different agencies interviewed. It should be noted that not one of those interviewed stated that developing a better understanding of the forensic evidence located on a scene could aid with the resulting court case. This is most likely due to the backgrounds of those individuals interviewed. All those interviewed were first responders and not forensic scientists, and as such they have a different focus and mind set compared with those involved in interpreting the recovered forensic evidence.

## 8.4 Conclusion

The questions posed to practitioners during the bus training exercise gave an insight into how forensic science is both viewed and implemented in a real world scenario. It should be noted again that those who were interviewed were only involved in the criminal investigation and not the later forensic evidence analysis and interpretation. The obvious gaps in priorities between forensic scientists and practitioners became apparent from analysing the responses. This is in part illustrated by the fact that practitioners seem to rely heavily on their own experiences and less on forensic evidence bases when drawing conclusions from a scene. This was further highlighted in that some of the practitioners wished that they had a better overall understanding of the forensic process to provide them with the knowledge of what would be the most useful not only in a criminal investigation but also in a forensic science prospective while investigating a crime scene. In not having a full understanding of the forensic process, personal experiences are then relied on by practitioners to understand and interpret the recovered evidence. As outlined repeatedly in the literature (NAS 2009,, PCAST 2016; Government Chief Scientific Advisor (GCSA) 2015; Edward 2009; Risinger 2009; Tully 2015; Saks and Koehler 2005; Cole 2006; Bowers 2006; Christensen and Crowder 2009) the need for evidence to be interpreted from a strong scientific standpoint is of the upmost concern within the field of modern forensic science. Having practitioners develop experiments to study areas where improvements are needed is critical, as it helps researchers develop scientific methods that will actually be employed within the field of criminal investigations and provide the scientific inputs towards any evidence recovered (PCAST 2016).

It is important to note that relying exclusively on practical experience to support evidence interpretation often leads to personal bias. This will inevitably impact the interpretations of the recovered forensic evidence (Mnookin et al 2011). Therefore, a balance of both the scientific and practical needs to be combined when designing forensic experimentation to ensure all aspects are included. This produces data similar to what is observed in the real world and can be easily applied to a range of forensic contexts. The next stage would be to ask the forensic scientists involved within each of the three agencies to see how they view the relationship between themselves and the law enforcement personnel that they work with. This would provide a clearer picture of how both practitioners and scientists feel about the current states of forensics in their

organizations. Since no forensic member of any of the organizations was present on the training exercise this was not done for this part of the PhD. If they had been, the researcher would have asked a set of similar question to obtain an understanding of how the forensic members view their relationship with their respective law enforcement colleagues.

The responses also indicated that training exercises like the bus experiment play an important role in helping first responders understand how these complicated scenes are processed, as so they are able to recover all forensic evidence. The need for materials that facilitate more of these exercises was stressed by several individuals on the site. This is worth noting, as it is not only vital that researchers have materials that are readily available, but also materials that are cost efficient to practitioners when designing training exercises. Several of the aims of this PhD could be applied towards addressing this concern, like scaling the experiments/training exercises or using gelatine instead of biological tissue as a target. The more training exercises available for practitioners to go to and learn about these types of criminal incidents, the more efficiently different agencies can work together. When the different agencies are able to work together in a more effective manner, the forensic evidence can be processed quicker and this helps to reduce the stresses practitioners noted occur on a scene like the training exercise (section 9.1.5).

The views of forensic science by practitioners and the importance of real world training exercise will be further discussed in the next chapter (Chapter Ten). Before moving to the discussion, several themes appear clear from the interviews. First, practitioners tend to pay close attention only to the part of the forensic process that is their direct concern. Second, whilst the agencies show much evidence of interacting together, they still appear to operate independently in terms of their concerns. This raises interesting questions about the extent to which practitioners actually need to understand/ have expertise in all elements of forensic investigations. Third, the detailed mapping requirements of different agencies could help determine the degree to which methods such as those developed (through the R program in this PhD) could be deployed for multiple purposes and how such methods could speed up search and recovery or assist with evidence interpretation.

## **Chapter Nine. Discussion**

The general and overarching question addressed in this thesis is whether it is possible to realistically represent the elements present at a forensic scene in experimental situations and, if it is, how those experiments can be best designed to produce an extended and usable evidence base that can be applied by both researchers and practitioners. This has been done within the particular forensic context of examining biological matter distribution following an explosion. An in-depth examination of the available literature highlighted the general challenges associated with forensic science, the opportunities provided by forensic archaeology and the lack of research into the spatial distribution of the tissue fragments created during an explosive event. This led to the development of a methodology that was applied to three separate explosive experiments. With the overarching goal of this research being the development of a realistic and usable evidence base, the three experiments were designed to address three separate research questions. How the collected data from these experiments addresses the aims of this research will be discussed in depth below. A final two research questions, on the use of forensic evidence in practice, was a theme discussed across several chapters but was particularly used to address information gathered from observation of a practitioner training event in which a bus was exploded.

### **9.1 Experimental summarization**

In the course of this PhD, a total of three different and unique experiments were conducted to explore the plausibility of developing an evidence base through the use of realistic experiments which focus on what happens to the tissue fragmentation during an explosive event. Although these experiments took place over the course of several years, the methodology and research questions were designed in such a way to keep continuity across each of the three experiments.

### **9.1.1 Comparison of the PhD experiments and Bus Training exercise**

It should be noted that the original goal of attending the training exercise was to observe how the larger and more complex bus explosive would compare to the experiments conducted during this PhD. Although the bus training exercise did not produced any fragmentation data, it is still an important aspects that should be discussed. The main similarity between this training exercise and the experiments that were conducted as part of this PhD was the use of the Waldron Springs Protocol to search the scene to record and, in theory, recover forensic evidence. Adoption of this protocol (outlined in section 2.3.1) meant that the search of all blast scenes could be quickly and efficiently conducted. All personnel understood what the overall objective for the day was supposed to be, what the chain of command was, and more importantly what their role in the process was. However, there are several major overall differences between the bus training exercise and the three PhD experiments. The first is that smokeless powder was used in the training exercise, not the military grade explosive that was employed in the PhD experiments. This is an important factor as the explosive power used in the training exercise was much less powerful than the C4 used in the PhD experiments (refer to section 2.2.2; Marshall and Oxley 2009; Morley and Leslie 2006). This lack of explosive power of the smokeless powder, coupled with the lesser overall amount of the explosive material used in the training exercise meant that the overall damage and resulting debris spread was markedly different. Secondly, the primary bus explosion took place within an enclosed, confined space, restricting the potential fragmentation spread (Held 1983). Thirdly, another difference that impacted the overall debris field was that in the training exercise the explosive was placed near the gelatine target rather than on it. This meant that the blast wave was directed in a different manner to how it was directed in the PhD experiments, likely impacting the debris field. This is illustrated by the fact that neither of the targets (biological (deer) or non-biological (gelatine)) in either the bus experiment or in the secondary explosion (that took place in an open space), experienced fragmentation. The blast was not powerful enough or placed closely enough (touching) to the targets to create that type of traumatic injury.

Although one of the two targets was exploded in an open environment like the PhD (the pipe bomb in the small bag) experiments, the larger of the two blasts took place in an enclosed environment. Although not necessarily any more realistic than an

explosive placed in an open area (see section 2.2.2 for more details), it represents a different type of explosive event. As detailed in section 2.4, in an explosion that occurs in an enclosed space the blast wave that is created reacts very differently than it would in a completely open area (Held 1983, 163). The blast wave created by the explosive material refracts off of the surrounding surfaces of the enclosed space and back into the enclosed space, creating a different overall blast wave than one created in an open space, where the wave dissipated as it travels. The blast and the resulting debris field are therefore more confined within the enclosed space, as the blast wave loses strength as it refracts back into the enclosed space. As observed in the video from the training exercise), the blast is mostly restricted to the bus structure itself, with the debris being expelled from the windows and doors after their having been destroyed.

The C4 explosive in the PhD experiments has more explosive power when compared to smokeless powder, resulting in the training exercise debris area being smaller when compared to the PhD experiments. The use of different types of explosive in a terrorist event have been discussed in greater detail in section 2.2.2, but in summary it is dependent on what is available to those conducting these types of attacks. In countries that are already undergoing conflict or if the terrorist members are part of well-funded organizations, it is easy to obtain military grade explosive materials (Quillen 2002; Morely and Leslie 2006; Asal and Rethemeyer 2008). In areas where there are restrictions on who can buy and hold explosive materials (for example the United Kingdom) homemade explosives are often used as they are the only materials available to conduct these types of attacks (Quillen 2002; Arnold et al. 2004; Kirby 2007; House of Commons 2006). Since this was a training exercise involving law enforcement personnel from a country (the United States), where restrictions are tight on who can and cannot obtain military grade explosive the use of a homemade explosive device was a more realistic scenario (as observed during the Boston Marathon Bombing (MEMA 2014)) and therefore suited to the task at hand of training law enforcement in a type of situation that they are more likely to observe. When examining the lack of fragmentation compared to the PhD experiments, it all comes down to the explosive power. The PhD experiments were designed to produce fragmentation, this training exercise was not. As to how this is reflected in a real world explosive event, it all goes back to how many variables are present within this type of event. The PhD experiments are most likely accurate as to

what occurs with military grade explosive and the bus training exercise to what would be seen with low power homemade explosives.

In the case of this PhD, one goal was to provide a first step in the development of an evidence base. There are many types of homemade explosives and since they are just that – homemade - they range in how they are produced and designed. To properly develop a primary evidence base, and to develop a reliable methodology, replicability – rather than reality – was of critical importance (Morgan et al. 2009; Morgan et al. 2008; Tully 2015); as such, homemade explosives contain too many different variables. If a homemade explosive was to be utilised in this research, then which chemical combination should be employed and how would the device be constructed? Furthermore, all of these experiments were conducted in a foreign country. This meant that transportation of needed materials to construct such a homemade device would be illegal. Building a homemade bomb is also very complex and highly dangerous as it is being constructed with already unstable chemicals being mixed together. A military grade explosive is not only stable material but also contains a chemical composition that is universal in nature and can be obtained anywhere in the world. For scientific purpose this limits variables across experiments and provides a material that can be obtained by other researchers. Further to the point of developing a primary level of experimentation that can be used to form the basis for an evidence base (Morgan et al 2009; Morgan et al 2008; Morgan and Bull 2007), as many variables as possible needed to be eliminated from the experiments. In this training exercise, the variables included: weather, target placement, bomb placement and bomb type, enclosed and open spaces, additional elements added to bob (bb pellets), bomb container, and using both biological and non-biological materials. To create a workable methodology that can be applied across experiments, the number of variables need to be extremely limited. This helps to not only keep things simple for consistency between researchers, but also helps to focus on a specific aspect of the forensic scene. A forensic scene, especially those which involve explosives, are extremely complex - much like what was created during the bus training exercise. To understand such a complex scene, the basics need to be understood first. This is what one of the aims of the PhD researcher was trying to observe, as this fundamental information is not currently well known. The bus experiment highlights not only how complex a real world forensic scene that involves explosive can be, but also how many different types of



primary experiments focusing on explosive events need to take place to create a workable evidence base that practitioners and researchers can apply to these scenes.

### **9.1.2 Aims and research questions: a review of the findings**

Five research questions were addressed in this thesis. Each question is addressed in turn below.

*Q1. Can data from scaled tissue fragment experiments be used to develop more evidence-based search and recovery methods?*

This first question asks whether the data from scaled experiments could be applied in the development of more evidence based search and recovery methods. In order to address the lack of an evidence base within a specific area of forensic science, sets of primary experimentation are done to establish what occurs in the simplest of circumstances before moving on to secondary experiments which explore more complex and specific circumstances through adding more variables (Morgan *et al.* 2009; Morgan *et al.* 2008). In order to do this, however, a large number of experiments needs to be conducted to establish a clear understanding of what occurs in even the simplest of circumstances. In exploring whether scaled experiments produce similar data to experiments with full scaled materials, the rationale was that this easier to set up and cheaper form of forensic experimentation which could facilitate the build-up of a workable evidence base through an increase volume of experimentation.

Several aspects should be noted as to the usability of the piglets within the context of this research question. As to the ability to produce a large amount of data, the piglets were much easier to obtain and to handle within the experimental context. Although the piglets were provided by an academic contact that the candidate had, this contact was provided these piglets free of charge from a local veterinary school. Due to stillbirths and accidental deaths, this institute tended to have a surplus of dead piglets that could be used for medical and scientific research. The large pigs in contrast had to be purchased before hand at great expense (£150 per pig). As to the handling of the piglets on site, they were significantly easier to handle and place into position. This was due to the fact that they were 1/6<sup>th</sup> the size and weight of the large pigs which required the use of a fork lift to place upright on the wooden stakes.

Given that the piglets were both easier to obtain and to handle on the site of the experiments, obtaining the needed primary experimentation for an evidence base would be an easier task than trying to do the same using the large pigs. However, as noted above in 9.1.1, the piglet data that was produced was dissimilar to what was recorded in the large pig experiments (see Dubois *et al.* 2017 and Appendix A). This may have been due to the fact the piglets were still partially frozen at the time of the blast, incorrect placement of the explosive device or it could be that the piglets are simply not a good substitute to the large pigs. It should be noted that only 5 separate tests were conducted in the course of this experiment. In order to better understand how the piglets act as a target substitute, more experiments would need to be conducted. These experiments should be done in a manner in which the piglets are fully defrosted and the researcher would need to be on the site when the explosive devices are placed on the targets to ensure consistency.

Within the field of forensic science experimentation, the sampling size is often smaller than in other scientific fields. Madra *et al.* (2015) examined 26 separate forensic experiments from around the world which studied decomposition using large pigs and the majority of the studies fell under 10 pigs in total. This is due to a range of factors, with cost and availability at the top of the list. Within the context of this research 10 separate tests was deemed enough to provide a sample size to result in statistical understanding. Although this number was not achieved during the course of this PhD research due to time and resource constraints, it is recommended that any future testing will be done over a longer period of time and therefore offer the opportunity to conduct an identified minimum number of tests.

*Q2. Can gelatine be employed as an alternative tissue target to biological matter in tissue fragment explosive experiments?*

The second research question was also designed to address the goal of expanding the evidence base and examined whether gelatine would act as a suitable alternative tissue target to biological targets in explosive experiments. With the challenges associated with obtaining biological targets and many ranges not allowing these types of targets to be used to prevent any sort of contamination, gelatine is a fairly easy material to obtain when compared to biological tissue targets and presents the option of not contaminating the range. This question aimed to explore an alternative target type which would allow more

researchers to conduct explosive research and expand the evidence database. In terms of ease of access, the gelatine blocks were purchased online and shipped to the candidate. In the case of both the large pigs and the piglets, several contacts had to be approached to explore the options of obtaining the tissue targets; a process that could take several months. This made the gelatine blocks the easiest of the target materials to obtain throughout the course of all experiments. However the results from the gelatine (in both the scaled and the normal size) produced results that differed from the piglet and pig data. As discussed above in section 9.1.1, the gelatine is not a perfect tissue substitute and this most likely impacted on how the fragmentation distributed during the tests.

Due to the ease of access in acquiring the gelatine and that more explosive ranges will allow this material to be used on them, further experiments into this material are needed. It should be noted that the costs of the gelatine block was not negligible; for both the large block and the 5 scaled blocks the total cost was £525. However, when compared to purchasing large pigs (£1650, with a discount), there are clear savings. Further, these blocks would also be cheaper than piglets, which while provided free of charge for this experiment, could also incur a significant cost.

Much like the above piglet experiments, only 5 tests were conducted using this material. With only 5 tests, a basic understanding can be gained but not a complete one. Future experiments should examine if adding a bony substitute into the gelatine helps the material to better resemble biological tissue. Much like the number of additional experiments described above for exploring the use of piglets, the same minimum number of 10 separate tests should be conducted. Once again this number was not achieved during the course of this PhD due to time and resource restrictions. It is again recommended that any future experiments be conducted over a longer period of time to accommodate for this number of tests. This would provide a larger data set with more of a potential to be statistically analysed to examine how gelatine blocks act in response to explosive forces.

*Q3. Do tissue fragment experiments with restricted variation present provide enough data that can be reliably applied to real world explosive events?*

The third research question examined if the experiments conducted in the course of this PhD provide enough context to be reliably applied to real world events. The

experiments developed for this project were designed to examine an explosive event with few variables present and done in a fashion in which addresses events of a generic nature (Morgan *et al.* 2009). This is a long way from the complexities present on an explosive event investigation. To understand what types of variables/complexity are present on these types of forensic scenes and how closely the results from the limited experiments conducted during this PhD are, the researcher attended a large scale explosive training exercise. In addition, during the training exercise a questionnaire was undertaken to see how closely practitioners use and employ forensic sciences, including the use of evidence bases. Through examining how practitioners actually use forensic science, some information on the relevance of the PhD results to real world events was explored.

Although the bus experiment was a distinctly different exercise from what was undertaken in the PhD experiments, it provided a valuable insight into how variable explosive events can be. There was no fragmentation (of either gelatine or biological materials) created during the course of the training exercise, even though there were three separate targets present on the scene. This was due, at least in part, to the less powerful homemade explosive used here (see Chapter Six for more details). As to how realistic this is when compared to the PhD experiments, the PhD experiments were designed as primary experimentation to establish the basis for an evidence base. The training exercise was just that, a training exercise. The law enforcement personnel chose just one type of situation that would be more common in western countries in which homemade explosives are used due to the restrictions placed on availability/ who can purchase military grade explosives. In other areas around the world, access to military grade explosive is easier to obtain and often used in these types of situations (see section 2.2.1 and 2.2.2 for further details). The PhD experiments were design specifically to be more general in nature as that is the purpose of primary experiments. Primary experiments are there to better understand individual variables before adding those variables together in secondary experiments which look at more individual instances (like what occurred in the bus training exercise). This is an important first step into developing forensic experimentation which looks at more specific scenarios like the bus training exercise. The bus training exercise also provided the researcher with the opportunity to explore other important variables that could be implemented in future experiments, including different types of homemade explosive or explosive events that take place in an enclosed setting.

This aspect of the PhD also provided the researcher with the opportunity to ask practitioners how they view forensic science and how they may employ it within their everyday work. The answer provided highlighted the gap between forensic science guidelines and what actually occurs in the field. The nature of the relationship that was developed between the researcher and the practitioners who helped to conduct the PhD experiments provided this insight. This connection is rare to have and one that needs to be fostered more within the two communities. Law enforcement will often have access to materials and spaces that researchers would not have access to without them and vice versa. In the case of this researcher's experiments, the connection with law enforcement opened up doors to explosive ranges and explosive materials that would not be otherwise possible. In response, the law enforcement practitioners were exposed to a different side of forensic science and could ask questions about the forensic science experimentation process, which opened up a dialogue of what may work or not work in the course of the experimental design. This back and forth collaboration is highly important as it helps to bridge that gap between practitioners and forensic science personnel. If more such relationships could be formed and fostered, it is likely that the whole of forensic science would benefit.

*Q4. What is the best process for comparing and contrasting the data gathered from each of the different tissue fragment experiments?*

The fourth research question looked at developing processes for comparing and contrasting the data gathered from different explosive events. The development of empirical methodologies has been discussed widely throughout this PhD (Mnookin *et al.* 2011, 11; Edwards 2010; Edwards 2009; NAS 2009; PCAST 2016; Cook *et. al.* 1998; Morgan *et al.* 2009; Morgan *et al.* 2008; GCSA 2015), noting how the experimental findings are documented and interpreted are key elements in terms of their potential use in forensic investigation. The R studio program that was developed to address this aspect of the PhD research was instrumental in analysing the data collected from all of the experiments that were conducted.

Several impacts of the position of the bomb on the tissue target prior to the device exploding could be identified using the R program. The resulting directionality of the fragmentation spread that was identified was directly related to the placement of the device on the target. The R program was also able to identify how far the fragments

travelled. This variable is directly tied to the high explosive power involved in creating the fragmentation. It is hoped with more experimental data this program can be built upon to provide even more detailed information. These experiments could examine the fragmentation spread created by homemade explosives or the spatial spread within an enclosed space.

The different aspects present within the data from different scenarios could help to form evidence bases reflecting what happens in specific situations. This could aid investigators in determining what occurred or likely conditions prior to the blast. Investigators could also use the R program's ability to identify those specific aspects about the situation prior to the blast occurring to assist with the identification of who may have conducted the attacks. As noted in section 2.2.1 and 2.2.2, attackers use the tools that are available to them and this will vary from group to group. By identifying what strategies certain groups or individuals are most likely to employ in these situations and then compare how those attacks look to the data collected in the evidence base, investigators could have another tool available to assist with assessing the plausibility of their involvement. It should be noted that the R program can be complicated to individuals who have never used the program and/or have little experience in computer coding. In order to make this program more accessible for practitioners to apply in their own investigations, it will need to be presented in an easily digestible manner. This is one aspect that could be explored in future work.

*Q5. How valuable do forensic science practitioners find forensic experimentation and resulting evidence?*

The fifth research question aimed to examine the views of the practitioners towards forensic science experimentation and the resulting data that is collected from those experiments. Once again with the aim towards developing workable scientifically focused evidence base (Mnookin *et al.* 2011, 11; Edwards 2010; Edwards 2009; NAS 2009; PCAST 2016; Cook *et al.* 1998; Morgan *et al.* 2009; Morgan *et al.* 2008; GCSA 2015), it is important to develop an understanding of what practitioners actually think of forensic experimentation. The law enforcement practitioners are on the ground every day and how they view and understand the need for forensic science experimentation is

important in developing not only better working relationships but also in making sure that the scientific based knowledge is actually applied by all of those involved in the process.

To address this final research question, a series of questions was posed to the practitioners during the bus training exercise. The questions were designed to examine how forensic science is both viewed and implemented in a real world scenario by law enforcement. One area that was highlighted in the responses to the questionnaire was that the practitioners tend to only use or apply forensic science within their direct concern during an investigation. This focus on only specific areas is further highlighted in that the different agencies tend to act independently of each other while on the scene. Each agency that responded to these types of explosive events have different primary focuses. For example, with an explosive event the FBI is primary focused on federal investigation that are associated with terrorism, while the local Sheriff's office will primarily deal with local police insinuations like the explosive risks posed by a methamphetamine laboratories during a police raid. Therefore agency independence in both the use of forensic science technique and what is focused on during the scene investigation is to be expected. This means that what aspects and forensic techniques the practitioners do apply are done in an exceptional manner and to the highest standard as they are focusing on different specific law enforcement situations. It also means that there can be a lack of communication between the different parties due to this extreme focus and it can mean that some aspects of the scene could be overlooked. It is essential that the different actors are drawn together in order to prevent this from occurring, as important forensic evidence could be missed which could impede an investigation or negatively impact the conviction of those responsible.

Output from the R program could perhaps be applied to aid communication. On the site, the different practitioners that are primarily focused on location of the various pieces of forensic evidence could bring together the various data points that they have collected and put it all together on the site through the R program. In further developed programs, the various information associated with those data points could also be included. For example, a data point that is associated with a piece of the explosive device could also record the material type, any identifying features, etc. Biological fragments could be weighed and photographed as well as being spatially referenced. This would help to not only bring the different agencies together to build an in-depth examination of what occurred on the site but also making sure that in real time the entire site is properly

documented. This real time information would not only be useful during the search stage but also in the later court stage in demonstrating within a legal context what occurred on the explosive site. The spatial location of various pieces of forensic evidence could be presented and aid in demonstrating to a court the impact of the resulting explosions. In having the R program on site, practitioners could also get involved with different aspects of forensic science. This would open up dialogue channels, helping to bring forensic science and law enforcement practitioners closer together. This will build better relationship which will only aid both communities.

Overall, the research questions were designed to address overarching questions concerning the application of forensic experimentation to the real world and the creation of an evidence base. In separating these overarching aims into five sub fields, different aspects of this question could be examined in greater detail. The first and second research questions highlighted that the different targets may not be suitable substitutes to the large pigs but more experiments are needed to explore this aspect of the PhD in more depth. This aspect of alternative target materials would open up the field of research and should be explored in greater depth. The third and fourth research questions focused on the data that was collected during the course of the PhD, the data analysed and how applicable the data and results are to real world situations. The main message here was that the experiments designed as primary experimentation to build up an evidence base are unlikely to represent the complexity of true forensic scenes. The experiments described here are only the first step in building up evidence. Once a foundation is established, further conditional variations might be tested and recording these in the R program could help to constantly update the picture to build up the reach of the evidence base. Lastly, the fifth question examined the views of practitioners towards forensics science. This question highlighted the lack of understanding between both forensic science and practitioners and the need for greater dialogue and collaboration. The general implications of the thesis findings that were highlighted in the review of the five research questions will be discussed in greater detail in the following section.

## **9.2 Implications of thesis findings**

The last section drew out the primary findings which addressed each of the individual research questions posed. Here, some of the broader themes that emerges from



these questions will be discussed, as well as their implications. Although the data collected during this research produced results that differed from the ‘baseline’ explosion using the large pigs, the findings nevertheless highlighted several important key aspects in the development of realistic experimentation to provide a basis for a realistic evidence base. Overall, these experiments helped to not only design a methodology in which to conduct explosive research but also the statistical program through which to compare the data from different situations.

### **9.2.1 Strength of forensic evidence bases**

One of the main goals for this project was examining the potential for building up an evidence base through the use of realistic experimentation. Although this goal is very broad, several key observations can be made. One of these is the realization concerning just how little evidence bases are actually used in investigations outside of a forensic science perspective. The questionnaire that was conducted during the large scale training exercise (see Chapter Eight for full details) highlighted that it is personal experience and input that law enforcement and the court relies on more than anything else. This influence is noted also throughout the literature as one of the major failures within the field of forensic science due to the impact of personal biases has on what should be scientific outcomes (Mnookin *et al.* 2011, 11; Edwards 2010, 8; Edwards 2009, 7-8; NAS 2009; PCAST 2016). In order for forensic science to truly be a ‘science’ it must first be approached with a scientific mind set and expanding the use of scientific evidence bases is but one step.

One of the problems with developing any sort of evidence base is the amount of time and resources that need to be undertaken in order for this to be done reliably. The research undertaken within the course of this PhD is a reflection on this. An evidence base can only be seen as an effective tool if it is built from the ground up. This first step can take several forms ranging from experimentation (as was the case here), computer simulations or even a (systematic) review of case studies. Within this PhD, experimentation was chosen as the basis for the first step towards developing a forensic picture of explosive events because it offers the advantage that tight controls can be enforced on the design and hence limits confounding variations. In choosing one very specific outcome variable (fragmentation spatial distribution spread), the experiments

could be designed to, wherever possible, limit any outside influences with the aim to obtain data that is focused just on the spatial distribution of the resulting fragmentation. Whatever this first step is, it has to be undertaken before any sort of complexity or realism is introduced (Morgan *et al.* 2009; Morgan *et al.* 2008; Morgan and Bull 2007). It is only when one examines individual variables and how they impact a scene, that when a more complex experiment is undertaken the behaviour of those variables can be truly understood. In the case of this experimentation, one variable (overall spatial shape of the resulting distribution) was examined across a range of different target materials and sizes. The data that was produced is only a small sample (statistically speaking) that needs to be extended in order to even understand this single variable. It is only when the smallest of the pieces involved in the whole forensic scene are understood can the complexity and variation that is present be fully comprehended. This small but important stage produces results that are then built upon in a range of future research. These range from the development of future experimentation (what works/ doesn't work; next logical experimental development, etc.), development of computer simulations or establishing the area that a collection of case studies should be focused on (Morgan *et al.* 2009; Morgan *et al.* 2008; Morgan and Bull 2007).

At this point however, the researcher cannot at this point with the limited data collected during this PhD recommend the use of the piglets or either of the sizes of the gelatine blocks in aiding evidence base development. The large pigs still appeared to provide the most accurate comparison to what would occur with (adult) human cadavers. The researcher suggests however that these substitute materials not be completely abandoned however as they still hold potential to, in the future, provide accurate data that then can be used in these types of experiments. In all the instances in which the substitute targets materials were tested, outside variables impacted how the targets reacted to the explosives forces (see section 5.4, 6.3, 7.5 for further details). More experiments should be conducted to truly explore just how these substitute materials compare to the large pigs.

However, it should be noted that it is not only important to focus on developing experimentation that is scientific in its aim but also seeks to address the concerns that are actually present in the field. One aspect of this research that was critical in the overall development of the experimental methodology was the input of the law enforcement practitioners who provided the explosives and the ranges for many of these experiments.

This was a relationship that is not often seen within this field (as outlined throughout the literature and more specifically in 2.1.5) and was important for this research. This information helped to guide the methodology into exploring options in both material choice but also in explosive size that practitioners, as well as researchers, could easily obtain. Although the data collected from the experiments indicated that the alternative materials and target forms tested here would currently be less suitable substitutes, it nevertheless helps to form an understanding of what works and does not work not only in terms of experimentation but also in law enforcement training exercises. It should be noted that the input of law enforcement was integrated here in a very organic manner. With future experimentation into this area of research, it would be recommended to connect this type of collaboration in a more formalized manner. This would allow for a better flow of information between both parties, which would only help with any future experimentation.

Another interesting aspect of this research was that it explored what the practitioners think are the main challenges within this specific area of forensic science in real life. As described in greater detail in Chapter Nine, one of the needs that the practitioners expressed was that a full search and recovery of the evidence on a forensic scene involving an explosive event is very time consuming. However, this is also coupled by an urgency that is placed on those working these scenes to quickly investigate in order to not only find out who conducted this event but also to return the public space back to normal to reduce public fears. They indicated that a more in-depth understanding of what actually occurs on these forensic scenes would be immensely important to aiding them in their investigations. One solution may be the use of the R program applied on the site in real time. This would help the practitioner on the site to develop an in depth look at where all the forensic evidence, not only any tissue fragments, is located. This would only add to the information that could then be applied to an evidence base.

It should be noted that within the parallel field of crime prevention, it is becoming more common practice for practitioners to apply evidence bases as tool to achieve their aims (Aos and Drake, 2013). For example, in collaboration with members of the Jill Dando Institute at University College London, the College of Policing has produced a crime reduction toolkit to provide practitioners with evidence bases to guide implementation of different crime reduction policies (College of Policing, 2017). The toolkit was created using the EMMIE (Effect, Mechanism, Moderator, Implementation,

and Economic cost) framework (Bowers *et al.* 2018). This is a framework designed to conduct a more comprehensive synthesis of systemic reviews examining the effectiveness of specific crime prevention approaches (Johnson, Tilley, Bowers 2015). It is these systemic reviews that provide the information that forms evidence bases that practitioners actually use, in this instance, to implement the suggested policies to reduce a range of crimes (Bowers *et al.* 2018). These evidence bases took time to develop and methods undergo extensive evaluation before they are recommended to and implemented by police forces to aid in reducing crime rates. A similar connection can be made between the time and effort that was put into place to develop these crime prevention evidence bases and the work needed to be conducted to produce similar tools in developing an evidence base for explosive events. In highlighting the similarities between crime reduction evidence bases and explosive events evidence bases an agenda can be set for developing it further with the needs of practitioners in mind.

It should also be noted that in a forensic context developed evidence bases often focus on confirming or excluding certain theories of what may have occurred at a particular scene. This is achieved through collecting corroborating or falsifying evidence. An example of this can be observed through the use of DNA evidence. The use of DNA is a common method within the field of forensic science to have establish whether individual(s) were possibly present at the site of a crime. This helps law enforcement to exclude or to have reason to further investigate an individual. This can only be achieved through vigorous scientific research and experimentation to better understand how DNA from various sources, including trace DNA, comes to be present at a scene (Meakin *et al.* 2017; Gehrig and Teyssier 2002). In comparison, in terms of use at the site of an explosion, an evidence base could be employed by law enforcement to help determine the size of the explosive used, the most likely placement, likely type of explosive, etc. Rather than specifically focusing on the presence/absence of particular individuals at the scene, this would help in eliminating or accepting different theories as to what occurred at scene. The uses of such an evidence will be explored in more depth in section 9.2.2.

### **9.2.2 From the crime scene to the court room – where would the evidence base be used?**

Although the results from the experimental element of this thesis concluded that different materials and methods tested did not resemble the large scale testing, it can be argued that the process positively contributed to understanding of the role of evidence. One of the positives is that these experiments have highlighted the different areas within the field of forensic science that they could impact. When an evidence base has been fully developed through the use of more realistic and complex experimentation, the information it contains can easily fit into a range of steps within the overall forensic science process. As discussed in depth within section 2.1.1, the forensic process can be broken down into four steps (Morgan and Bull 2007):

1. An investigation of the scene
2. Analyses of the evidence/data collected
3. An interpretation of that evidence/data
4. Presentation of both the findings and the associated interpretations to the appropriate parties

When examining where the potential data from an evidence base developed along the lines of the research conducted during this PhD would fit into these steps and stages, one area is in the investigation of the forensics scene itself (stage 1 above). As discussed in detail in section 2.3.1 and in Chapter Nine within the context of the response to the questionnaire, a forensic scene created by an explosive event is very complex and time consuming to process. If a better understanding of what happens during an explosive event can be gained by practitioners, the process of search and recovery of the evidence can be conducted in a more efficient and effective manner. As discussed in throughout the thesis, the time constraints that are often placed on investigators on these scenes can be immense. In the context of the research which focused on the overall spatial distribution of the fragmentation, if the likely locations of fragments are better understood, then when practitioners are on a forensic scene the majority of their effort and focus can be placed into those focused areas of the scene. One of the main observations that was recorded across all of the experiments was that the majority of the fragmentation was located at or near the blast centre. As noted in the literature (see section 2.2.2) and in each of the

chapters that discussed the experiments conducted (see Chapters 5.4, 6.3, and 7.5), this is due to the limitation of the blast wave itself. Although an incredible powerful force, it quickly dissipates and when coupled with the resulting vacuum of negative air pressure (created by the surrounding environment trying to return to a stable air pressure) which tends to suck objects back towards the blast centre, and limits the range of the overall fragmentation. As a result, this leads to the majority of the fragmentation being located at/near the blast centre. This suggests that practitioners should focus the majority of their efforts in searching for and locating evidence at/ near the centre of the blast site.

The data obtained from the PhD experiments can also be applied to the analysis of the evidence recovered from a forensic scene (stage 2 above). The R program that was developed during the course of this research was based around developing an easy to use statistical tool that would produce understandable statistical outputs aimed at multiple aspects of the explosive event. This enabled comparative analysis to be undertaken across all the explosive events. When investigating these events, one key aspect of the investigation is understanding the placement of the device in relationship to the target/s. One of the conditions that was constant across the experiments in this thesis was the placement of the device on the target and the resulting directionality of the fragmentation distribution. Across the experiments, the placement of the device directly on the centre of the target lead to the result spread of the fragments being out and away from the centre. This made the overall distributions of each of the tests look much like a pie piece shape. Although the reasoning behind the placement of the device on the target was in obtaining the maximum fragmentation distance possible, it also led to the observation that the placement of the device impacts dramatically the overall shape of the distribution. This indicates that there is a potential to explore the likely placement of the device and likely location of the target by exploring the directionality and shape of the resulting fragmentation distribution.

The results can also be more widely applied to the interpretation of the evidence collected from the forensic scene (stage 3). This is tied directly to the development of a comprehensive realistic evidence base, as many more variables will still need to be tested to develop a more comprehensive understanding of what occurs during an explosive event. The methodology designed during this PhD could be applied to a range of future tests done on large scaled biological targets aimed at interpreting the causes of certain forensic scenes. The PhD experiments only examined what happened during an explosive

event conducted with C4 or a military grade explosive and with that material placed directly on the target. However, if more testing was undertaken that explored the spatial shape, distribution and range of fragments from different explosive devices, different placement of those devices and different configurations of such as multiple targets, this could begin to develop a deeper understanding of what most likely occurred in a range of circumstances. This would involve comparing collected data from an explosive event scene with the evidence base to see which situation present in the overall base it most likely resembles. In doing this, the range of variables that were outline above can be inferred to as being present on that specific forensic scene.

In terms of using spatial distribution comparison in this way, the level of interpretation also falls into stage 3 of the forensic science process. Any future testing would need to explore not only the range of variables previously discussed but also the many problems associated with investigating an explosive event. As discussed in detail in section 2.3.1, these scenes are incredibly complex and often evidence is already distributed and contaminated before the investigation can take place. This can be caused by first responders tending to victims, victims having evidence on them and leaving the scene, etc. This will often lead to evidence movement and transfer from its original position.

The second (the analysis of the evidence/data) and third (the interpretation of the evidence/data) stages of the forensic process would need to address this aspect in any future experimentation. This information can also be presented to a court of law in a manner which can be easily understood by those within a legal context and without personal biases (see stage 4). In developing the unique R program more and making it more user friendly, the important statistical data that it produces can be used to explain to a wider audience what the scene was prior to the blast in a fair and unbiased manner.

### **9.3 Assumptions, limitations and next steps**

Before continuation or expansion of the type of forensic science research reported here, it is important to address and assess several aspects of the approach taken. These concerns are not only important in highlighting the potential limitations of this research but also in exploring the best possible methods for any future work. In particular, any

future experimental work would need to address these changes and be modified to limit these concerns.

### **9.3.1 Practical research limitations**

There are several areas of concern that should be discussed that relate to experimental design and set-up. One of these is that these experiments were conducted in an outside environment and meant that the weather conditions could not be controlled for. As noted throughout all of the experimental chapters, DuBois *et al.* 2107, and in Appendix A, at each experiment there was some sort of weather event that impacted or prevented an element of the experiment taking place. Ranging from extreme wind and rain to high heat and to a low cloud ceiling, all of these weather conditions were variables that impacted the experimental outputs but could not be controlled for. The extreme wind and rain that occurred during certain tests impacted the results in that the maximum distance observed and the overall spatial shape of the fragment distributions were more extreme than tests conducted during periods of calmer weather. As for the low cloud ceiling, as noted in Chapter Six which examined the effectiveness of employing large gelatine blocks, this weather event was one of the factors that prevented the use of larger quantity of explosives.

Another area of concern which impacted the data that was collected during the course of this PhD is that the experiments were conducted in the United States and not in the United Kingdom (where the candidate's research institution was based). Although conducting the experiments in the U.S. allowed for a close working relationship with practitioners and greater ease in obtaining the explosives, it also meant that any coordination that needed to occur in the planning steps and the purchasing of materials took place in a different time zone from where these activities would take place. It also meant that the gelatine models (see section 3.2.1) that were created in order to reduce not only the cost associated with conducting this work, but to also add a simulated bony structure to more closely resemble the biological tissue targets, could not be used. There was no realistic manner in which the large models could be shipped to the U.S. from the United Kingdom and used. If the models could have been shipped to the U.S., then the logistical challenges of a space to actually make the gelatine and then cold store the completed gel blocks would have required addressing. There was no useable space that



could have been used to achieve this. This meant that the gelatine blocks that were employed for the purpose of these experiments did not have an internal bony structure which most likely impacted that resulting fragment spatial distribution of those targets. This is an avenue of research has already been explored in other areas of explosive research (Smith *et al.* 2015; Mahoney *et al.* 2017) and should be integrated into any future experimentation.

Another challenge that was present in the course of conducting these experiments was that the explosive ranges used dictated the amount of explosive that could be used- or a 'range limit' was established. This aspect impacted the large gelatine experiment the most as the range where this experiment was conducted had a range limit of 1.5 pounds of explosive and hence like-for-like comparisons between this type of target and the large pigs was not possible. The large gelatine experiment was also impacted by another challenge present throughout these experiments cost. Due to the expensive nature of having to buy the gelatine blocks instead of creating them only one large block could be purchased at a cost of 360 British pounds. This meant that this experiment was hindered on multiple fronts and analysis for this test relied on a sample size of 1. Cost also impacted other tests as well, in that only a small number of experiments could be conducted within the budget. For example the scaled ballistic gel blocks cost 50 British Pounds (for a total of 250 British pounds) and had to be shipped to an academic contact of the researcher (who was also kind enough to house the researcher for the duration of these experiments). Due to the expensive nature of travelling to the U.S. as well, only one set of experiment could be conducted a year and this limited the amount of time that could be spent on the explosive range. This meant that the high cost of implementing these experiments placed a significant range of challenges in conducting these experiments.

Another limitation that should be mentioned is the impact of relying on the bus training exercise as a realistic explosive event scene. This limitation is also linked to using the views of the practitioners that were interviewed during the course of the training exercise as representing the more general views of forensic science from a police investigator perspective. The researcher did not attend a real post blast investigation during the course of the PhD. Therefore what actually occurs during an investigation or what practitioners actually think may not be what was observed during the PhD research.

### 9.3.2 Research design limitations

It is important to discuss both the strengths and weakness associated with the fundamental approach that was chosen to address the research questions posed by the researcher. An animal-based model was proposed as a valid approach to exploring the dynamics of an explosive event that includes a human subject at its centre. As discussed in the literature review (2.5.2, 2.5.2.1), pigs are often employed within forensic science experiments as a human substitute due to the many similarities that exist within their tissue structures. The use of large pig models within this context is a reasonable one since it has been tested within many forensic contexts and has proven to be reliable. It should also be noted that within this assumption, the large pigs were used as a type of ‘gold standard’ to which all of the substitute tissue targets were compared. Since large pigs have been used throughout forensic science as a substitute for humans (Christensen *et al.* 2012; Schoenly *et al.* 2007; Catts and Goff 1992; Passalacqua and Fenton 2012), then to compare other types of materials that could be used as a substitute to the large pigs is at least partially justifiable.

Within the course of the PhD experiments, only one gelatine block was tested within the same perimeters as the large pigs, whereas a greater number of experiments were possible at the scaled size. As an interesting aside it might be that given the piglets behaved differently from the large pigs, we might speculate that perhaps human cadavers of different ages might behave differently in explosions. In any case, all the experiments were limited in number and more data is needed to truly understand how the gelatine acts within this context and this can only take place with more experimentation.

Another aspect that should be discussed is that this PhD chose to test these research questions using primary experimentation. There are alternatives to doing physical experimentations, such as running computer simulations. Computer simulations are already employed in a range of crime science fields, including examination of the likely effectiveness of crime reduction policies (Johnson and Groff 2014). One method of computer simulation that would be most appropriate for further exploring this type of explosive research would agent based modelling (ABM) (Johnson and Groff 2014). In this type of computer simulation, ‘agents’ are employed to test out a range of situations and variables with trial being run numerous times. There are several advantages that come with using any type of computer simulations. One, the cost to run the computer

simulation is significantly less than those cost associated with conducting experiments. Second, computer simulations allow a researcher to run many multiple experiments that can include many different types of variables. There are also, as might be expected, some disadvantages to using computer simulations. One major disadvantage is that the data used within the computer simulations to run those types of experiments need to be based on real world observations and/or well-established rule systems and theoretical principles. These real word observations and rule systems can only be gathered through controlled experimentation. Existing cases studies that are conducted into various subject areas are often based on very specific events that have already happened and contain variables that have not been controlled for. In this sense, only real world experimentation can be used to gather the data sets that can then be employed within a computer simulation to produce large amounts of data that can be used to further any evidence base.

### **9.3.3 Possible next steps and recommendations**

There are several possible steps that could be taken towards achieving the aim of developing a usable forensic evidence base for explosive events. One of the most obvious of these would be to conduct many more experiments. As discussed in depth throughout the literature section, the ability to produce more useable evidence bases relies on developing primary experiments that explore individual variables. This creates a base of understanding of these individual variables that can then be applied towards examination of the interaction of those multiple variables that would be present in more realistic and complex experiments (Morgan *et al.* 2009; Morgan *et al.* 2008; Morgan and Bull 2007). In terms of the work conducted in the course of this PhD, the limited number of experiments conducted would have to be expanded on. This would also include experimentation that would replicate the conditions and variables present during the course of the PhD (Morgan *et al.* 2009; Morgan *et al.* 2008; Morgan and Bull 2007). This replication of what has already been conducted would provide the opportunity to gain a better statistical understanding of what happens within the fragmentation spatial distribution that was primarily observed during these experiments. Such a basis can help with the identification of exceptions, with prediction, and with baseline parameters for computer simulations. For example, if those involved risk management design got to better understand the resulting damage of an explosion in various situations, then they

may be able to implement certain features that may prevent that resulting damage from occurring or reduce its impact. This may be examining how a blast would act in an enclosed space and then developing means to reduce the impact of the blast in the surrounding area.

In order to achieve the necessary increase in experimentation, relationships with practitioners could be developed. Since the downscaling and changing of the experimental targets did not produce the results that would indicate that either works as a suitable substitution to the large pigs, then reaching out to the practitioners could be useful. They have access to a range of explosives, range locations and often animal targets (e.g., the large biological target in the bus experiments was a deer provided by the local wild life service). If future opportunities were used as a joint training exercise/ forensic science experiment, then both sides could benefit and it could present a solution for many of the practical problems that are associated with this type of forensic experimentation. If the opportunity presents itself, then a similar questionnaire to the one that was conducted during this thesis should be conducted. This could lead to the response being codified and analysed statically in a more social science approach. This would provide a more in-depth examination into the relationship between practitioners and forensic scientist.

Another avenue that deserves further exploration is a means of controlling for the unpredictability present when conducting these experiments in an open outdoor environment. If a large enough indoor space could be found (where the blast wave would not be impacted by refracting off of the walls or ceiling), then the impact of weather conditions on the resulting spatial distribution could be removed. Exploring the use of gelatine could potentially be continued by examining if adding a synthetic bony structure into the gelatine makes the resulting spatial distribution similar to the large biological tissue targets. This is a method (adding synthetic bony structure to gelatine) that is currently being explored in wounds caused by ballistic weapons (Smith *et al.* 2015; Mahoney *et al.* 2017). Other experiments could start to examine additional variables, which would aid in developing the secondary experimentation and build-up of the evidence base (Morgan *et al.* 2009; Morgan *et al.* 2008; Morgan and Bull 2007). One such set of experiments could examine how the spatial distribution changes with the use of multiple targets and/or multiple explosives. This would add to the realism of the experimentation but also in further examining what types of trauma has been highlighted

in several case studies and other explosive experiments (Kitulwatte and Pollanen 2012; Leibivici 1996; Hull and Copper 1996; Covey 2002; Ramasamy *et al.* 2011; Proud 2013; Marshall 1988; Christensen *et al.* 2012) (see section 2.5.1 for further details).

## **Chapter Ten. Conclusion**

This PhD aimed to address the overarching goal of developing a realistic plan for experimentation in order to build up a workable evidence base that can be applied by practitioners in relation to forensic scene investigations focusing on explosive attacks. In order to achieve this, several sets of experiments were conducted. Each was designed to address research questions developed to break the overarching goal down into manageable sections. The five research questions were as followed:

1. Can data from scaled experiments be used to develop more evidence based search and recovery methods?
2. Can gelatine be employed as an alternative tissue target to biological matter in explosive experiments?
3. Do tissue fragment experiments with restricted variation present provide enough data that can be reliably applied to real world events?
4. What is the best process for comparing and contrasting the data gathered from each of the different experiments?
5. How valuable do law enforcement practitioners find forensic experimentation and resulting evidence?

The method development is one of the main outputs, while the main implication is that further testing is required in order to gain a true statistical understanding of what is actually occurring during an explosive attack. The methods developed were unique in that they were developed to address the challenges associated with this new field of explosive research. The other main output was the development of the R program, which was a novel way to examine the data produced during the PhD experiments. Given that the field of forensic science is moving in the direction of applying empirical evidence to forensic situations over personal experiences/biases, developing a better understanding into this area is of importance to the field. The experiments that were conducted during this PhD were a first step in collecting enough data to understand just one of the variables present

in an explosive event- spatial distribution of fragments. In conducting more experimentation but still using the developed data analysis techniques, the data from future tests can be compared and contrasted. It is through this comparing and contrasting of the data that an evidence base can be built through realistic experimentation that can then be exploited by practitioners and researchers in the field of forensic science.

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## **Appendix A**

Several sets of experiments had already been conducted prior to the start of this PhD research and were both part of two separate master's degree projects. These tests helped to establish the baseline knowledge and requirements that would be used in the course of the PhD experiments. Although the actual experiments were conducted during the course of previous degrees, the data that was collected earlier was used during the first year of the PhD to inform the development of the R studio program that was used to analyse the data that was collected during the rest of the PhD. It also formed the comparison data which represented the distribution of fragments for full-sized pigs.

### **A.1 Overview of Previous Experiments**

Two sets of experiments were conducted during the course of an MSc and MRes degrees. Both aimed to establish the basic methodology that would be employed in the course of the PhD experiments and to collect enough data to form a base opinion of how to proceed in future experiments. The experiment that was conducted in the course of the MSc degree employed five large pigs that were exploded with 1.5 kgs of military grade explosive and the data that was collected focused on examining the fragment weight and length. Although this latter avenue of data investigation was not continued (fragment weight and length), this set of tests formed the basis of the methodology that was employed in later tests. The experiments that were conducted as part of the MRes degree employed the same methodology and experiment set-up that was established in the MSc experiment but focused on the overall spatial data, along with how to collect and process this new type of data set. During the MRes experiment nine large pigs were used along with 3 kgs of military grade explosive. Although a few basic statistics were performed on the spatial data, the goal of the experiment was to provide a stronger experimental methodology and to identify areas for future studies.

The nine deceased pigs used in the course of this experiment were purchased for 150 pounds per pig directly from a local farmer who raised them to sell as meat produce.

For these experiments, the explosive materials that comprised the bomb were placed together and wrapped with duct tape (Figure A1). The finished bomb was then placed on the front and centre of the pig. This composition of the bomb was chosen for two reasons. The first was that by having the explosive material bound closely together, the resulting forces are produced in a central location that then spread outwards from the centre point. This was the easiest way to create the most powerful force that would produce the maximum tissue fragmentation. Secondly, it was also less expensive as it only used one primer charge to create the explosive train that produces the explosive force. The explosives were purposely not placed in any type of container or device, allowing for the examination of what happens to the tissue fragments with no other material involved.



**Figure A1.** A photograph demonstrating the composition of the explosive prior to detonation.

The pigs were placed directly upright onto a wooden stake to resemble a suicide bomber (Figure A2). As observed in Figure A2, the position of both the pig and the explosive was chosen as it allowed for the examination of the maximum distance obtained by the resulting tissue fragments. This would be possible as all of the force of the explosion was position in one direction against the pig tissue. The overall direction

that the pig and the explosive faced varied due to the difficulty in getting the pigs upright on the stake. Although the direction between the different tests differed, the statistical program that will be described in greater detail later on allowed for the tests to be compared by rotating the data sets. It should be noted that before each of the test was performed, the wind speed was recorded to document how the overall distribution was impacted by the weather (see Table A1).



**Figure A2.** A photograph representing the completed experiment set-up prior to detonation.

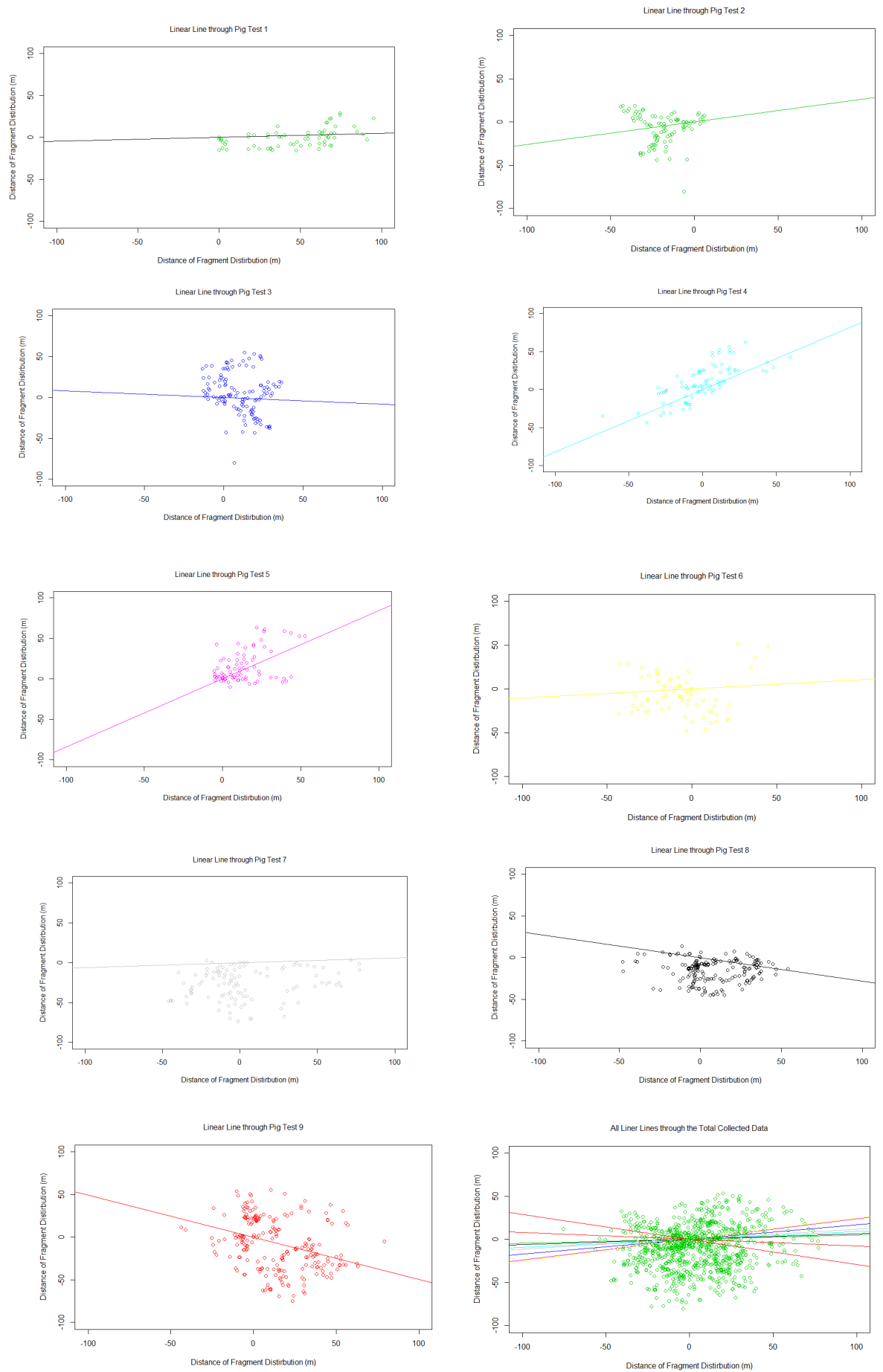
Test Number	Recorded Wind Speed (MPH)
Test 1	30
Test 2	20
Test 3	6
Test 4	7
Test 5	7
Test 6	6
Test 7	3
Test 8	3
Test 9	4

**Table A1.** A table outlining the recorded wind speeds during each of the 9 tests.

This study employed the Waldron Springs Protocol and is described in detail in section 4.1. This method is designed for fast recovery of evidence and for plotting of fragments in mass disasters, which are complicated scenes with many moving parts. The acquired data was then uploaded to a Global Imaging System (GIS) program. This data was then used to create a map of the distribution, which produces an empirical database that can be used by investigators in both the forensic examination of the scene and in the later evidence interpretation. This process substantially reduces the risk of human error in the recording of the tissue fragmentation distribution.

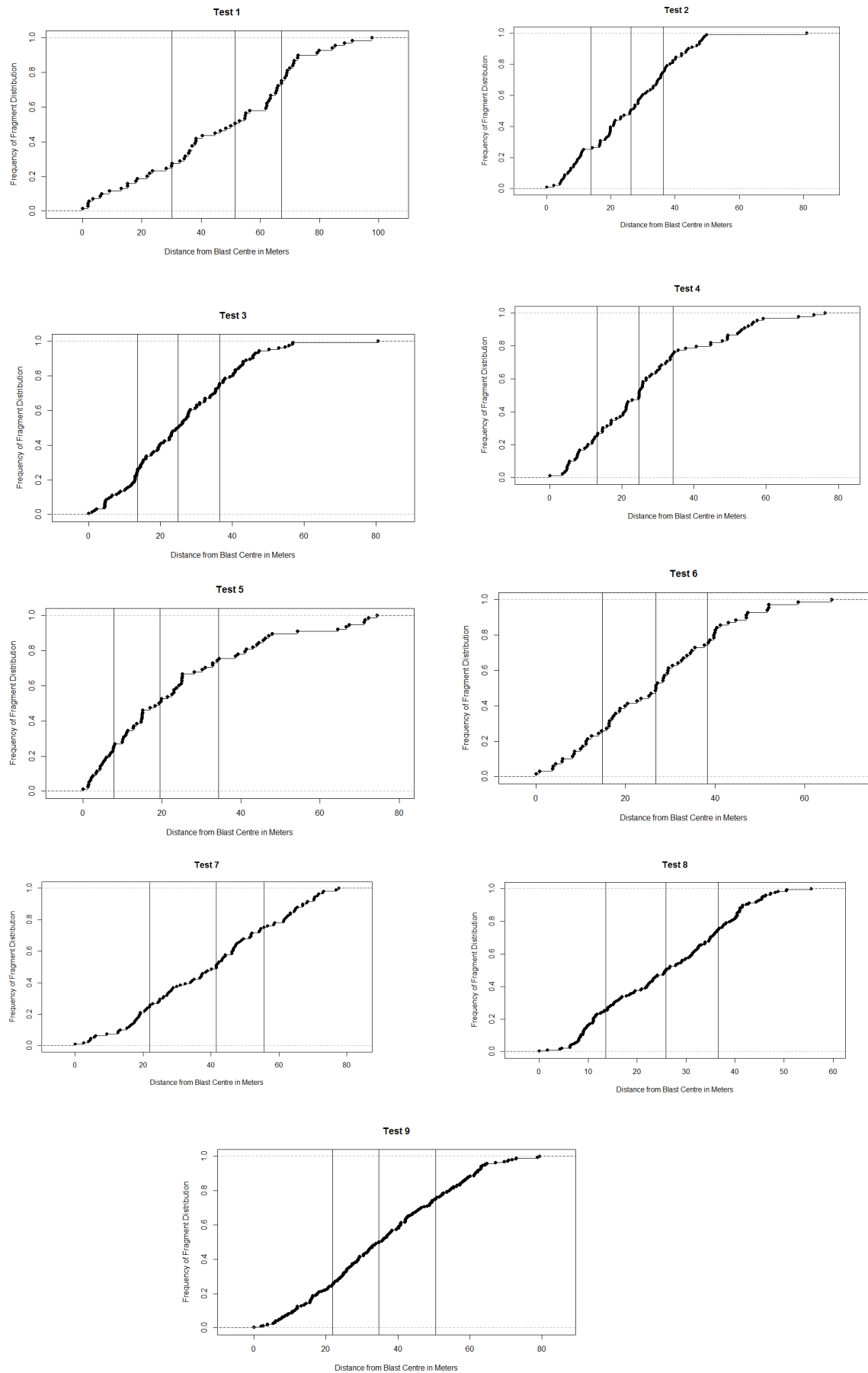
## **A.2 Development of R Studio Program**

During the first year of the PhD, the spatial data that was collected during the course of the MRes was used to form the basis of the R studio program that was later used in the analysis and comparison of the data that was collected during the PhD experiments. The first step was to develop a way to compare and contrast the individual experiments to each other. A particular challenge was that due to the way that the site was laid out and attempts to prevent commingling of the fragments, the pigs and the bombs were not all facing the same way. This meant that the spatial data from each test was directional different, which made the process of comparing and contrasting the data sets difficult. To address this problem, a linear regression line was employed and can be observed in Figure A3.



**Figure A3.** The linear regression line plotted through all nine data sets.

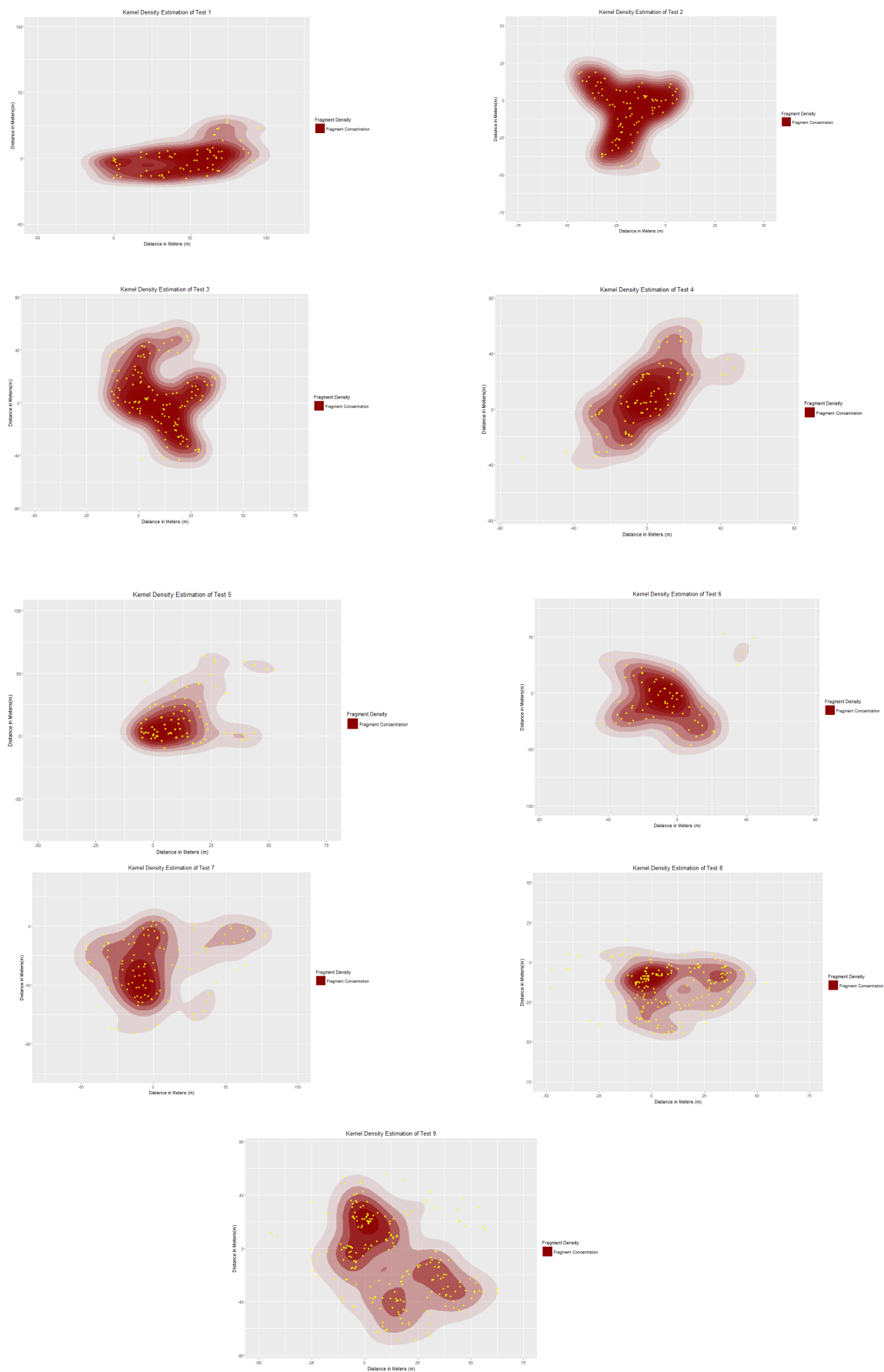
This is more fully described in section 4.4 of the methods chapter. Although normally used to compare data attributes to each other, the use of a linear line through the data was used as a means of tying the data points within their spatial position. In keeping the data points in the same locations and angle to each other through, the program was designed to rotate the lines (and the tied data points) so that each test could be layered on top of each other and compared with the general direction of blast a constant. The cumulative density of each of the tests was then calculated and plotted with the percentage of fragmentation observed (by Q1, Median, and Q3 respectively) (Figure A4).



**Figure A4.** The cumulative density graphs of the nine test sets with vertical lines representing the percentages of fragmentation found within Q1, Median and Q3 amounts respectively.

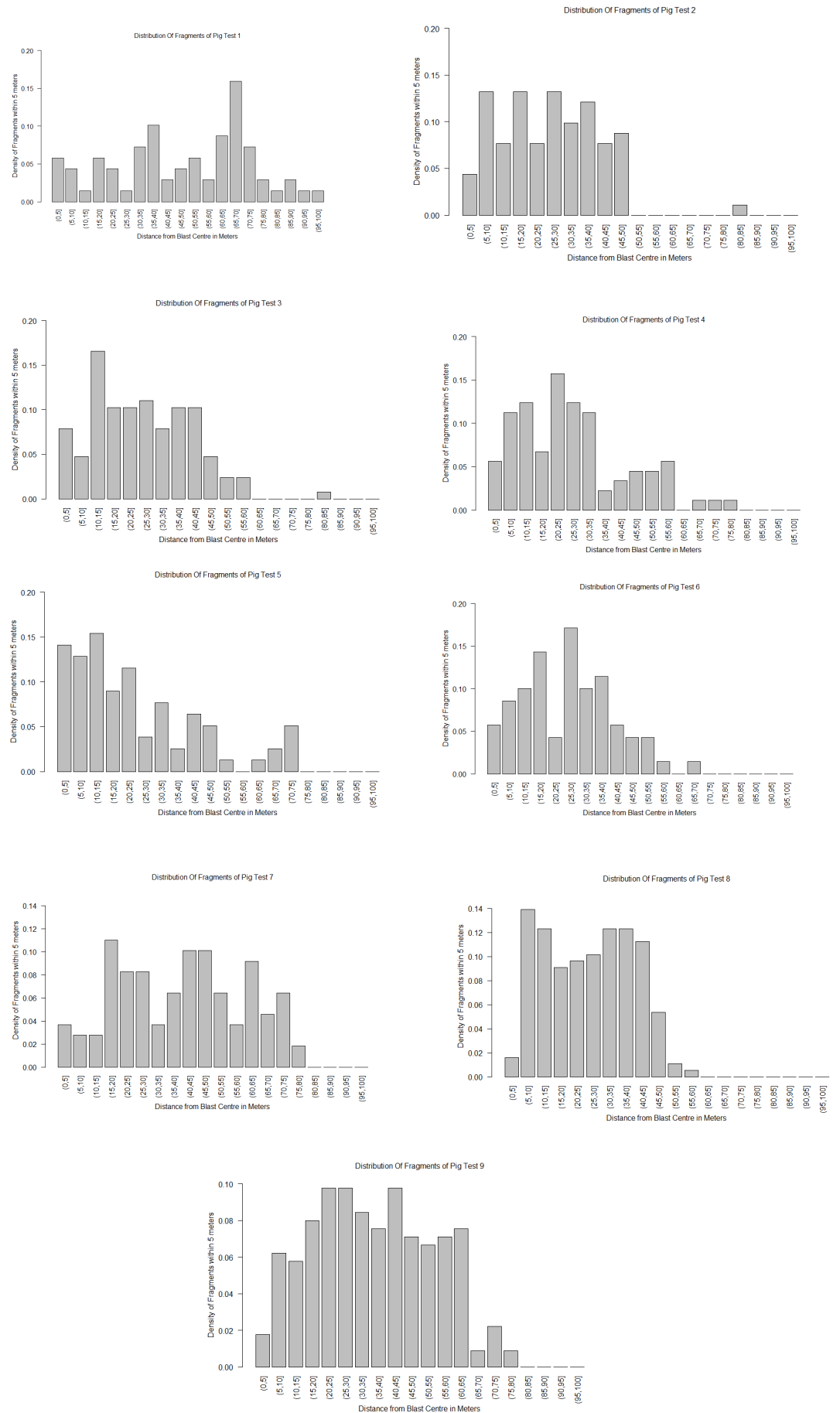
This was done to aid in identifying the areas where the majority of the fragmentation was located and to form an idea of any possible location similarities across the test. It should be noted that across all nine tests, 50 percent of the fragmentation (in most cases) was collected prior to the 50 meter mark. The next stage in the development of this program was to develop a manner in which it was possible to identify the areas of clustering of the fragmentation. The aim for this area of the program was to identify areas of highest fragment concentration to further develop a more accurate and efficient search and recovery method that can be applied in time sensitive and/or dangerous situations. This was achieved through a combined use of a kernel density estimation (KDE) test, which identified areas around the blast centre where the majority of the fragments were located or 'hotspots' of fragmentation (Figure A5).





**Figure A5.** All of the KDE tests that were conducted on the nine data sets.

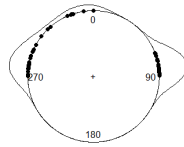
The KDE is a statistical test was chosen because of its ability to visual demonstrate the areas where the fragmentation clustered and the areas where there was very little to no fragments. Across all nine tests, the overall spatial distribution pattern is one of clustering around the blast centre, with a decrease in fragmentation density as the distance from the centre increase. The use of density bar plots was the next stage in the statistical analysis (see Figure A6). This test demonstrated the density amount of the fragments every 5 meters moving out from the blast centre.



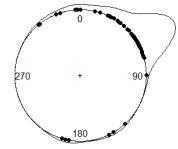
**Figure A6.** All of the density bar graphs conducted on all of the data sets.

This was another statistical test that was conducted with the aim of visually identifying the density of the fragmentation per 5 meters. This test was also conducted to try and observe any similarities across the nine tests. The fragmentation is greatest at and near the blast centre, with a gradual decrease in fragmentation density as the distance from the centre increase. This result is one that is similar to the one observe in the KDE tests in Figure A3 and demonstrates clustering of the fragmentation at/near the blast centre. The data was then processed through the next stage of the program which applied circular statistics (described more fully in method chapter section 4.4) to examine the impact of the placement of the bomb on the target and the resulting directionality of the spatial position of the fragments (observed in Figure A7).

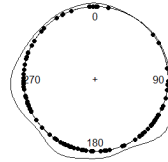
Circular Density of Fragment Distribution of Pig Test 1



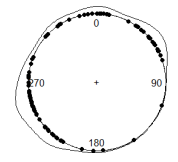
Circular Density of Fragment Distribution of Pig Test 2



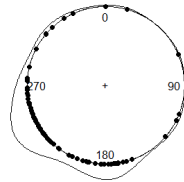
Circular Density of Fragment Distribution of Pig Test 3



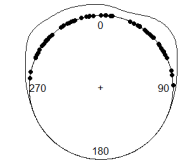
Circular Density of Fragment Distribution of Pig Test 4



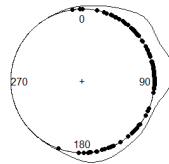
Circular Density of Fragment Distribution of Pig Test 5



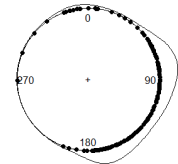
Circular Density of Fragment Distribution of Pig Test 6



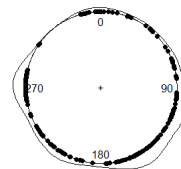
Circular Density of Fragment Distribution of Pig Test 7



Circular Density of Fragment Distribution of Pig Test 8



Circular Density of Fragment Distribution of Pig Test 9



**Figure A7.** All of the circular analysis of all the collected data sets.

This is achieved by visually examining the direction of the blast spread based on a 360 degree rotation around the blast centre. The degree area that has the highest fragment concentration is directly related to the placement of the explosive device on the tissue target. Since the placement of the explosive device was always placed directly on the centre of the pig chest, the variation of the angle of highest fragmentation density is due to the different direction that the pigs were tied up on the wooden stakes to hold them upright. Following this, this process is further reinforced through conducting Rayleigh's test of uniformity on the data sets to statistically identify how evenly the fragments fell around the blast centre and the resulting sums can be observed in Table A2 which included the other summary statistics.

Test Number	Q1 Distance	Median Distance	Q3 Distance	Maximum Distance	Number of Fragments recovered	Rayleigh Test of Uniformity
1	30.01	51.39	67.20	97.71	69	0.8593*
2	12.85	26.26	36.37	81.02	91	0.598*
3	13.54	24.84	36.37	80.54	127	0.366*
4	13.11	24.75	34.13	76.35	89	0.3178*
5	7.84	19.45	34.28	74.44	78	0.6658*
6	14.87	26.67	38.24	66.03	70	0.4554*
7	21.96	41.55	55.66	77.68	109	0.6562*
8	13.59	25.89	36.61	55.57	187	0.6242*
9	21.78	34.67	50.47	79.34	225	0.2952*

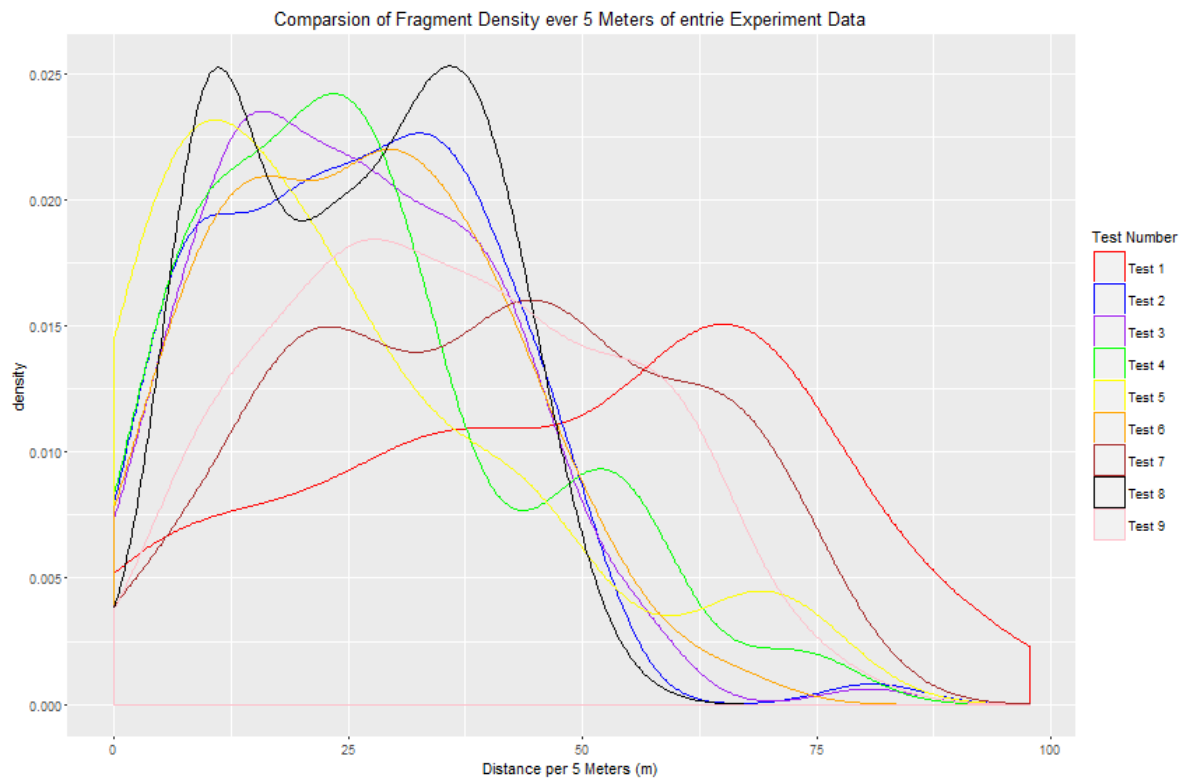
**Table A2.** Summary statistics including the Rayleigh's test of uniformity for the collected test data (\*  $p < 0.01$ )

The results demonstrate that the resulting spread was heavily impacted by the placement of the bomb on the target and therefore the data is directional in nature. The p-value of zero or lower indicated a rejection of the hypothesis that the spatial data fell equally around the blast centre. In table A3, the results from the Watson-Wheeler test are displayed below and were used as another means of applying circular statistics to exploring if there were any similarities in the angle of fragmentation around the circle.

Test Number	1	2	3	4	5	6	7	8	9
1		100.74*	76.34*	2.03	73.17*	48.64*	2.81	19.84*	68.24*
2	100.74*		166.99	79.21*	140.11*	42.25*	54.53*	162.79*	191.60*
3	76.34*	166.99*		17.32*	20.91*	101.10*	61.03*	50.03*	7.14*
4	2.03	79.21*	17.32*		17.33*	29.46*	75.72*	116.67*	38.92*
5	73.17*	140.11*	20.91*	17.33*		90.58*	107.23*	118.54*	56.82*
6	48.64*	42.25*	101.10*	29.46*	90.58*		45.87*	95.03*	110.92*
7	2.81	54.53*	61.03*	75.72*	107.23*	45.87*		11.32*	39.90*
8	19.84*	162.79*	50.03*	116.67	118.54*	95.03*	12*		22.95*
9	68.24*	191.60*	7.14*	38.92*	56.82*	110.92*	39.90*	22.95*	

**Table A3.** Watson-Wheeler test of the nine pig tests with stars demonstrating results with a significant p-value (p value <.05\*).

The Watson-Wheeler test was conducted to statistically observe the impact that the placement of the explosive material on the test subject has on the resulting fragment distribution by comparing the circular distribution of two tests to each other. Those results that do not have a significant p- value are those in which the placement of the explosive material was similar to the test it was compared to. Any p-value that is less than .05 is indicated with a star; those tests do not demonstrate a similarity in the angles that have the greatest concentration of fragmentation. Lastly, all of the data fragmentation density that was compared can be observed in Figure A8.



**Figure A8.** The fragment density of each of the collected data sets.

This graph shows that there are differences observed in the distance at which the main percentage of the fragments is located. All of the tests demonstrate a similar peaking location and where the majority of the fragments are located.

### A.3 Discussion of Results

The mean maximum distance of 76.5 meters can be explained in the context of how the force that is produced by the explosion decreases after the initial chemical reaction. After the chemical reaction that creates the blast wave there is a huge increase in surrounding air pressure as the blast wave moves away from the blast centre at supersonic speeds. There is an increase in the environmental pressure, which soon decreases as the blast wave moves away from the centre of the blast (Covey, 2002; Wightman and Gladish, 2000). It is here that the momentum of the tissue fragments ends and they began to fall to the ground. Although the initial force produced by the explosive blast is strong enough to create maximum fragmentation of the pig, the distance the blast wave was able to allow the tissue fragments to travel was still below the 100 meter distance. Another aspect that would impact the resulting distance obtained by the fragmentation is the



resulting vacuum that occurs as the environmental pressure returns to normal (Born, 2005; Held, 1983). This sucks the fragmentation back towards the blast centre and therefore limits the distance that the fragmentation can travel. Within the published literature there are few examples about how far forensic evidence associated with these types of explosive events will travel. Instead most are focused on the chemical distribution or case studies (Kelleher, 2002; Abdul-Karim et al, 2013; Kirby, 2007; MEMA, 2014; HOUSE OF COMMONS, 2006). The ability to scientifically examine how far the tissue fragments will travel is an important step in adding to the forensic evidence base.

In addition to being limited in terms of the distance of travel, the tissue fragments also tend to be directional as demonstrated by the Rayleigh's R statistics and the distribution visualisations. This implies the influence that the placement of the bomb will have on the resulting spatial spread of the fragments. This observed pattern was one in which the blast force directionally 'pushed' the tissue away and back from the centre of the blast, causing the wedge-shaped pattern observed in the spatial maps. The Watson-Wheeler results along with the KDE visualisation reveal conditional variation between tests. For example, Tests 1, 7 and 9 were obviously impacted by higher wind speeds (see Table A1). This differs from what was observed in Tests 1, 4 and 7 which appeared to have a more similar shape, which was impacted not only from less powerful wind speed but had more similar overall placement of the charge or debris?. It is obvious that accounting for these variations is important in interpreting the resulting forensic evidence.

Another aspect of this data analyses was to examine the density of the fragmentation and try to establish an idea of what distance a certain percentage of total fragmentation would be located. This was done using two different statistical tests, the density bar graph and a cumulative density chart. In both statistical tests there are similarities between all nine tests that deserve discussion. As observed in the density bar graph in figure A6, the cluster of the fragmentation and therefore the location of the majority of the fragmentation occurred around the centre of the blast before it decreases as the distance from the blast centre increases. This observation is examined further in figure A8 or the cumulative density charts where the percentage of fragmentation per 25, 50 and 75 percentage is calculated. Across all nine tests, 50 percent of the total fragmentation is usually located below 50 meters. The ability to identify this clustering of

the fragmentation in and around the blast centre is an important aspect of helping to developing an accurate forensic evidence base.

Overall, although there are differences that are observed between each of the tests, there are enough similarities to draw overarching conclusions for all of the tests run during this section of the experiment. It is in these similarities, which range from the impact of the weather, to the impact of the explosive device placement, to the clustering around and near the centre, which can be applied to the overarching goal of these experiments; to create a database based on experimental data that can be employed by professionals in the field to aid in both their investigations but also in the forensic interpretation of any collected data. This set of data was collected during an experiment that was designed to provide a baseline to which future data sets could be compared and contrasted. In the course of the experiments that produced the data that was analysed, outside variables (i.e. different explosive types, different explosive placement, clothing on targets, etc.) were removed or at least mitigated to provide an understanding of what occurs during an explosive event to the tissue target. In applying this base line data and the implications obtained from it to the other studies that have been conducted as part of this PhD, a more in depth understanding of what occurs to the tissue in an explosive event can be identified and lead to an empirical evidence base which can then be used by practitioners in the field.

